Degree Thesis

Design of Machine Elements

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DEGREE THESIS	
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Abstract:

Machine elements are important components that allow for the running of machinery. These include a range of components broadly categorized as "universal elements" such as springs, bearings, chains, gears, pins, belts, bolts and keys, and "special elements" such as turbine blades, aircraft propellers and crankshafts. These components are integral building blocks for most types of machinery. Among the Machine Elements, gears are the most widely used for various purposes within engineering due to their myriad uses and ease of production. Gears come in different shapes and sizes that fall into four general categories "spur", "helical", "bevel" and "worm". Machine Element is a broad topic, so focus was given to a single type of machine element, that is gears, as a representative of the machine elements. Here too though, gears come in a variety of forms as such focus was given to a single type of gear known as a Planetary Gear to represent the gears and as such represent Machine Elements. The objective of the thesis is to review and analyse the relevant literature on the design of Machine Elements, by focusing on gears as representatives of Machine Elements, their design principles, and design methods. Then choose a single gear type and use computer-aided design (CAD) software to model and simulate the performance of the designed chosen gear under various operating conditions and loads. During the CAD process, a Planetary gear was designed consisting of Ring, Carrier, Sun and Planet; with the chosen material for all the gears being Gray Cast Iron. The assembled Planetary gear was put through two contact analyses (first between the Ring gear and a single Planet gear and the second between the Sun gear and a single Planet gear) and a torque simulation between a Planet gear and the Ring gear. The Contact analyses and the torque simulation showed four results each; Stress (MPa), Displacement (mm), Strain and Factor of Safety [FOS]. The torque simulation was done via a series of torques ranging from 1 MPa to 60 MPa to get a series of results. The first contact analysis results (Ring-Planet gear) showed a max stress (σ) of 128 MPA between the contacting teeth, a max displacement (δ) of 0,21 mm, a max strain (ε) of 0,0013 and a minimum FOS of 1,9. The second contact analysis showed σ_{max} of 126 MPa, δ_{max} of 0,039mm, ε_{max} of 0,00175 and a min FOS of 1,6. The torque simulation results showed a series of results depending on the torque applied; for the abstract, the results for the max torque of 60 MPa shall be given; that being a σ_{max} of 169,1 MPa, δ_{max} of 0,004mm, ε_{max} of 0,0027 and a min FOS of 1,16. The methodology detailed the steps taken in modelling and simulating a chosen Machine Element while the results conveyed an example of a positive result from a hypothetical Planetary gear as a form of Machine Element.

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SYMBOLS AND ABBREVIATIONS

T	Torque (Nmm)
P	Power (kW)
N	Speed of rotation (RPM)
F_t	Tangential Force (N)
F_r	Radial Force (N)
F_n	Normal Force (N)
F_a	Axial force (N)
d	Diameter (mm)
ASTM E647	American Society for Testing and Materials E467
ALM	Additive Layer Manufacturing
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CNC	Computer Numerical Control
DXL	Deep X-ray Lithography
FEM/FEA	Finite Element Method/Finite Element Analysis
FDM	Fused Deposit Modelling
LIGA	Lithographie, Galvanoformung and Abformung
MTTR	Mean Time to Repair
Nd:YAG laser	Neodymium-doped Yttrium Aluminum Garnet laser
PLA	Polylactic Acid
RP system	Rapid Prototyping system
SLA	Stereolithography
SLS	Selective Laser Sintering
STL	Standards Triangle Language
Yb:YAG laser	Ytterbium-doped Yttrium Aluminum Garnet laser

FOREWORD

I would like to take the moment to express my gratitude to Mathew Vihtonen for his guidance and support, without whom this thesis could not have been written. I would like to thank all the researchers, writers and students who came before me from whose papers and books I gained immense knowledge and understanding; without them this thesis would be baseless.

I would also like to take the moment to thank the entire Materials Processing Technology (now Mechanical and Sustainable Engineering) departments at Arcada who throughout the years have taught me and shaped me into who I am now. Last but certainly not least, I would like to thank my friends and my family whose support and advice had made the difficult journey more pleasant.

1 INTRODUCTION

1.1 Background

If all creatures have their strengths, then that of humankind is the ability to think, converse and create with the usage of our exceptional minds. One of the greatest feats of mankind is in the creation of items, and eventually, technologies with the need to make things easier for oneself, protect oneself or, sadly, destroy. With our intellects, we humans began from creating small, simple yet deadly hunting weapons to eventually creating items for the increasing of farm produce as well as means of helping us defend such productions from others who wished to take it by force. Time moved on, and humankind began to develop more advanced machinery, eventually landing Neil Armstrong and the Apollo 11 team on the moon on July 20th, 1969 (NASA, 2019). Yet all of these, from the earliest horse-drawn carts to the newest state-of-the-art automobile, all had something in common: the usage of machine elements.

Machine elements will be discussed and defined in detail in the coming chapters but for now, it is imperative to understand the importance of this concept. As mentioned before, machine elements have been, and still are, important because they allow and keep machines connected and/or running. To this day, machine elements remain an integral part of every form of machinery and other equipment made, for human society's betterment (and at times detriment). Hence why it is important to understand not only what machine elements entail but also why they must be studied, experimented on and, eventually, improved upon to realise a safer, more advanced, and greener world. In this thesis a Planetary gear was designed and analysed using the library function of SolidWorks, the Planetary gear stood as a representative for the Machine Elements as covering all the machine elements types is beyond the scope of this thesis.

1.2 Objectives

The fundamental focus and aim of the thesis is to review and analyse the relevant literature on the design of machine elements, by focusing on gears as representatives of machine elements, their design principles, and design methods. Then to choose a single gear type, Planetary Gear, and to use computer-aided design (CAD) software to model and simulate the performance of the designed chosen gear under various operating conditions and loads. The thesis will be broken down as follows:

- Detailed literature review on the theory, design, production, and analysis of gears (detailed information on gears as material elements followed by details of the chosen gear, that being Planetary gear).
- The design process of a Planetary gear using SolidWorks CAD software.
- Simulation and analysis of the Planetary gear using FEM via SolidWorks.

1.3 Compliance with the degree programme theme

Material Processing Technology (renamed to Mechanical and Sustainable Engineering) is the study of “modern material technology and processing as well as sustainable product design and development” (Arcada, 2022). It also holds in high importance teaching students how to design, analyse, and develop smart and sustainable products by selecting the right engineering material. The program is about innovation, creating new and necessary sustainable products, knowing what materials to use and how to assess and analyse the product(s) to evaluate its functionality.

Likewise, this thesis also focuses on not just the theory of material elements but the designing and analysing of a material element (i.e., planetary gear) to apply the theory. This thesis, therefore, is in full compliance with the degree programme of Material Processing Technology (or Mechanical and Sustainable Engineering).

1.4 Relevance to existing knowledge

As discussed in the introduction, machine elements are an integral part of machinery as well as human technological and societal advancements, even more so in the present. Currently, the importance and necessity of machinery cannot be understated due to their key role in multiple sectors of the modern world such as factories, construction, transportation, computers and so much more. Every form of convenience in the present requires some form of machinery which in turn cannot function without the usage of machine elements (such as gears for more complex machinery). This thesis is not the first to discuss such a topic nor is this topic even remotely “new.” Yet it remains important.

A thesis written by Peterscu et al. on “Gear Design” gave clarity on determining the importance of gears in machinery as well as their efficiency, forces acting upon gears as well as the velocities and powers. The paper focused on identifying how to best optimize the gear mechanism and improve the functionality of the transmissions with gears by reducing, if not eliminating, the interference of the gear teeth.

Another thesis by Thapa Suman (2020) on “3D printing of Automobile Power Transmission Systems using tough PLA” also discussed the gears and their usage in modern society. In this thesis, the author aimed to design, and 3D print a functioning automobile power transmission system using Tough PLA as the printing material, which they succeeded in.

These theses, as well as the myriad others on the topic, should be proof enough for the importance and relevance of the topic discussed in this thesis.

2 Literature Review

One of the objectives of the thesis was to "review and analyse the relevant literature on the design of machine elements, by primarily focusing on gears as representatives of machine elements, their design principles, and design methods". In this section the general definition, design, manufacturing processes and failure modes of machine elements in general will be explained before the focus shifts to just gears (their design, parts, types as well as their manufacturing process) and eventually further shifted to just the Planetary gear.

2.1 Machine elements

2.1.1 Definition

A fantastic book on machine elements titled "Analysis and Design of Machine Elements" by Wei Jiang puts it succinctly: "*A machine is a device that employs power to accomplish the desired function to benefit humankind*," yet its machine elements that allow the machines to complete these functions in the first place.

Machine elements are defined as individual components or parts that are used to construct machines or mechanical systems. They are an integral part of all forms of machinery from the smallest of watches to the largest of oil rigs; in which they are carefully designed and arranged to collaborate with one another for the machine to complete its tasks. Machine elements are broadly categorized as "universal elements" such as springs, bearings, chains, gears, pins, belts, bolts, and keys which are used in a variety of machinery and "special elements" such as turbine blades, aircraft propellers and crankshafts (Jiang, 2019). They are the "small" yet important parts that, when they work together, make the machine as a whole move and work.

2.1.2 Machine design

Machine Design is the single most important activity in the mechanical industries (Voland, 2003). Machine design is, simply put, the designing of mechanical or machine products and there is no real sense in delving into the meanings and semantics behind what material elements are without explaining their design processes. *Machine design is the art of envisioning, creating, and developing a brand new or improving on an existing mechanical device for the fulfillment of human needs, with due regard for resource conservation and environmental impact* (Jiang 2019).

Designers and engineers are expected to conceptualise and choose the best shapes, dimensions, and materials for new (or updated) products despite the usually limited information, ambiguous and (at times) contradictory requests from clients and/or one's own company while also working within a constraint (financial, legal, environmental etc.). On top of that, machines will, in most cases, have more than a single solution (in terms of design) for their specific function, since design is the act of creating and choosing from countless concept designs; this all depends heavily on the designers "knowledge, previous design method and design philosophy" (Jiang, 2019)

To design a machine element, therefore, one must have a clear understanding in applying scientific knowledge, professional judgement, empirical information, and ingenuity in solving practical problems, while also honing a keen sense of responsibly and professional work ethics in accordance with the “Code of ethics of engineers” (ABET, 1977). The rather extensive knowledge and skills expected from a mechanical designer when designing not just material elements but all forms of machinery, includes the following (Jiang 2019):

- Professional understanding of mathematics, mechanics of materials, statics, stress and strength analyses, kinematics, and mechanisms to facilitate load.
- Advanced CAD/CAE (Computer Aided Design/ Engineering) or FEM (Finite Element Method) techniques.
- Familiarity with engineering materials and their properties.
- Materials processing, heat treatment and manufacturing processes
- Understanding of tribology, fluid mechanics, heat transfer
- Project management skills, creativity as well as complex problem-solving capability

2.1.3 The process of designing machine elements

With the basics of machines design, and its requirements, understood; it is now time to discuss the actual process an engineer is likely to undergo when designing a machine element. This roughly falls into four main steps (with smaller sub steps); Identification of the machines task, assumptions and decisions, design analysis and evaluation followed by drawing and documentation. (Jiang 2019).

I. Design and identification stage is, simply put, identifying the requirements and variables for the design and how the element(s) interacts with the surrounding component(s) before selecting the best machine element type (i.e. bolt, gear etc.) for the required application and function.

II. Assumptions and Decisions. Here, the material and heat treatment required should be selected first and if necessary, an initial design for the element should be proposed. The choosing of the material and heat treatment beforehand is important as the engineer should have all the required material property data for any future calculations, these can be collected immediately from the charts and tables that can be found in design books. As for the initial design, though it may not be required immediately, it does help as the initial design proposed would show any dimensions and shapes that might affect the performance or stress analysis. With the material and heat treatments identified, and a set of initial design set aside (if needed), the next step would be to consider that the actual mechanical system must be idealised and simplified in order to facilitate load analysis; one must also keep in mind the potential failure modes and decide on a relevant design criterion.

III. Design analysis and evaluation stage involves the performing of strength and rigidity tests in order to analyse which of the basic geometrical dimensions of machine elements (previously chosen) meet the performance requirements against failure. Should the performance not meet the requirements, the initial design, dimension and/or material(s) must be revised after which the design process must be repeated before another analyses is performed. Repeat if another failure occurs, or until a satisfactory result is reached.

IV. The final stage is the drawing and documentation phase which begins after a satisfactory result has been reached. In this stage, the designer must begin the process off using the calculated dimensions in the making of detailed drawings with the consideration for manufacturing, assembly, maintenance, and standardisations as well as the purchasing, usage, and disposal of the product. Indeed, modern designers and engineers must keep in mind the sustainability of their products and how they can be recycled and reused in accordance with circular economy.

Other angles to keep in mind includes the design specifications for all elements, intolerance, fits and finishes as well as standards, codes or preferred dimensions for purchase and manufacture.

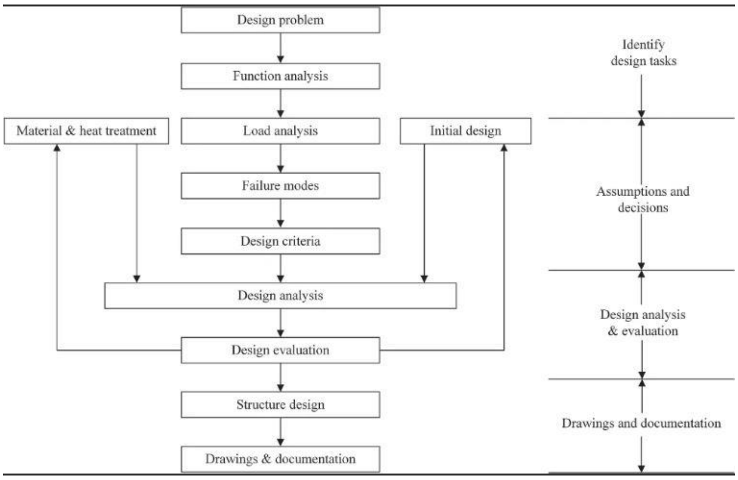


***Figure 1**: Design process of machine elements (Jiang. 2019)*

2.1.4 Safety and common failure modes

It is common knowledge for engineers that machine elements (and indeed all products) must ensure efficient and safe function by being designed and produced in a manner fit for their purposes. Of course, the act of a prototype failing is completely normal, in fact, according to Matthews et al. (1998,), *"Most engineered products will have a large number of possible ways that they can fail (termed failure modes)".* Some of the more commonly observed mechanical failure modes includes deformation, yielding, fracture, fatigue, pitting and spalling, wear, scoring, scuffing, galling and seizure, corrosion, fretting, creep, buckling etc. (Jiang, 2019*).*

In this thesis the Planetary gear will undergo contact analyses and torque simulation. The contact analysis will be a static contact analysis, hence a possible failure for the planetary gear (should it be subjected to stress beyond its yield point) could be plastic deformation or yielding of the contacting gear teeth.

2.2 Gear design

Machine elements include a host of different objects used in the running of a machinery such as bearings, shafts, keys, couplings, fasteners, and gears. In this thesis, the focus will be given to a specific type of material element, that being “gears,” which play a significant role as “transmission machine elements” (Madhusudan, 1987).

The term “gear design” is quite self-explanatory; yet, despite the simplicity of the phrase, the process of designing and eventually testing a gear is anything but simple. This is because a variety of parameters are involved in the designing of gears which correspond to the previously discussed design process of machine elements. Since gears are designed to transmit a certain amount of power for a specified speed condition of a wheel, it will need a few “primary inputs” which need to be considered during the design phase; that being power, pinion speed and gear ratio. This must be considered in the design of all kinds of gears.

In essence, gears fall into four large categories spur, helical, bevel and worm. For this portion of the thesis, focus will only be on spur, helical and bevel gears.

2.2.1 Parts of a gear

Despite there being many different types of gears, each with their unique traits and advantages, all gears have some basic similarities: teeth, bearing and partition.

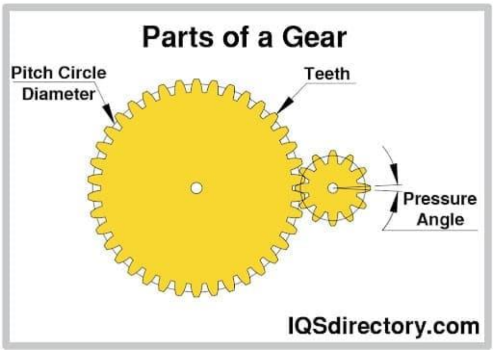


***Figure 2**: Parts of a gear (Industrial Quick Search)*

The gear teeth or “toothed crown” is a part of the gear which allows for the transfer of movement from one gear to another. A gear tooth is made up of three parts (fig. 3 below):

- A “top land”, which is the outer and upper parts of the tooth.
- A “face-and-flank” or “face-of-the-flank”, which are the upper and lower parts of the side faces of the tooth. These sides are important in connecting one gear with another.
- A “bottomland”, which is the lower part or the intermediate area between two teeth.

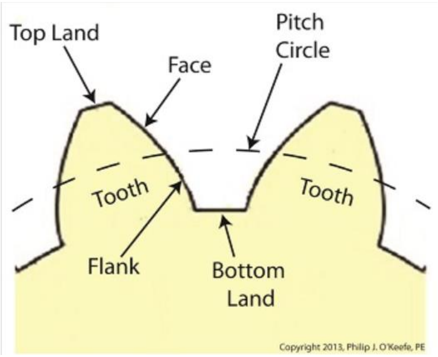


Figure 3*: Gear tooth terminology (*Top Land | Engineering Expert Witness Blog*, n.d.)*

The next part of a gear is the "bearing", which is the part of the gear which the shaft would be connected to. Finally, the third and last part of a gear is the "partition", which is the space between the toothed crown and the bearing.

2.3 Spur gears

2.3.1 Definition

Spur gears, known also as straight-cut gears, are the simplest of gears consisting of a cylindrical disk with teeth projecting radially (fig. 4) and are, therefore, the least expensive of all gears to manufacture and can be manufactured to close tolerance. They are used to connect parallel shafts that rotate in opposing directions. As for their overall function regarding spur gears, R Keith Mobley, in his book "Plant Engineer's Handbook", puts it best:

It gives excellent results at moderate peripheral speeds and both load produces no axial thrust. Because contact is simultaneous across the entire width of the meshing teeth, it tends to be noisy at high speeds. However, noise and wear can be minimized with proper lubrication. (Keith, 2001).

Figure 4*: Spur gear (Industrial Quick Search)*

Spur gears are cylindrical and contain straight "teeth" parallel to its rotational axis (fig.3) and are designed to function, mostly, by rolling contact rather than siding contact. The rolling contact produces less heat and yield (often) up to 99% mechanical efficiency (i.e., the effectiveness of the machine, in this case the gear, in transforming the power input to power output).

Spur gears are categorized into three main classes: "external tooth", "internal tooth" and "rack-and-pinion"; of these, the external tooth variety is the most common. An internal spur gear combined with a standard spur gear pinion creates a compact drive mechanism for transferring motion between parallel shafts rotating in the same direction.

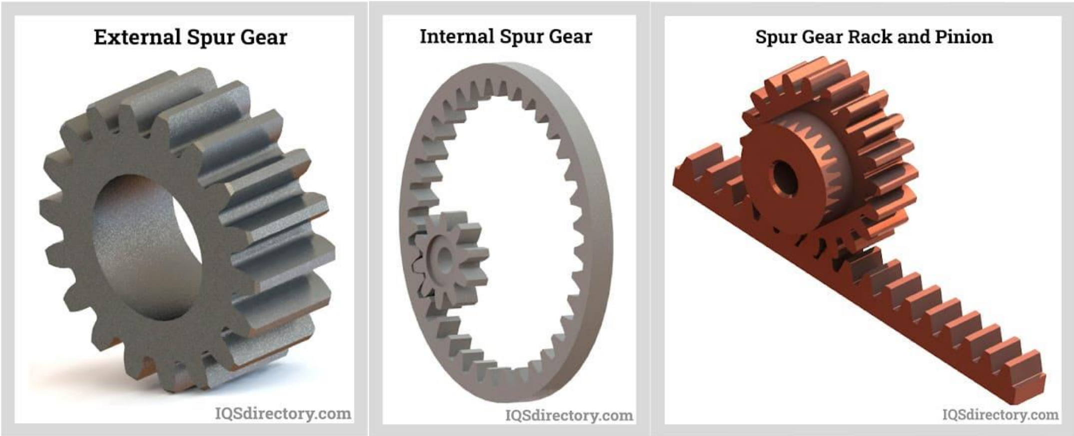


***Figure 5**: External, internal and "rack-and-pinion" Spur gears (Industrial Quick Search)*

2.3.2 Forces acting on a spur gear's teeth

For spur gears pitting and tooth breakage are the two most prevailing failure modes. Gears should be able to run their expected life without significant damage; for this it is imperative that there be a proper power transmission. This is usually guaranteed by the tooth "surface contact strength analysis" and "tooth bending analysis", starting with "force analysis" (Jiang, 2019). While it is important to discuss all the different failure modes and methods of analysing the strength of the spur gear (and all other gears in this thesis), they are beyond the scope of this thesis and so focus will be given instead to the forces that act upon the spur gear teeth and the possible impacts they may cause on the teeth if one is not vigilant.

When a pair of gears are operating, the teeth of the driving "pinion" pushes on the driven teeth, thus creating a torque on the gear; power is also transmitted due to the gear's rotation (power transmission involves the application of torque during rotation at a given speed). The relation between the nominal torque (T) and the transmitted power (P) is governed by the following equation:

$$T = 9550\frac{P}{n} \qquad (1)$$

T = Torque (Nmm), P = Power(kW), n = Speed of rotation (RPM) (Jiang, 2019)

The reduction in the rotational speed of a gear will conversely increase the torque transmitted to the gear shaft, hence an inverse proportionality. This is because, if friction is neglected, the power transmitted by the pinion and gear are the same.

Yet, that is not the only possible force acting upon the gear; consider the following fig. 6 below:

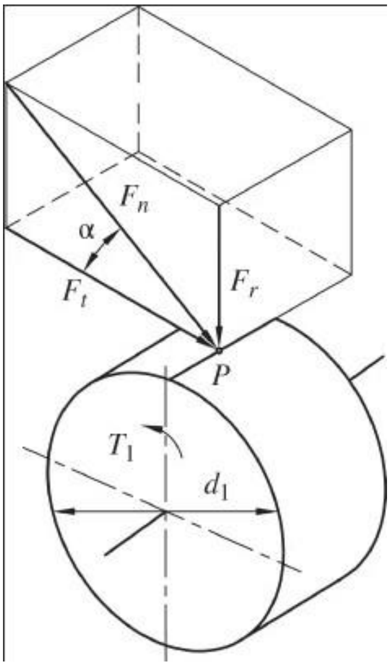


***Figure 6**: Force acting on spur gear (Jiang, 2019)*

The figure shows a pinion rotating counter-clockwise while transmitting a torque. Assuming the forces act upon the midpoint of the width of the face and neglecting friction; the force can be resolved into two components, a tangential force (F_t) and radial force (F_r) in the radial direction. According to Jiang 2019, *Tangential force is directly related to power transmission; therefore, this force is often called "transmitted force"*.
Using the moment equilibrium at the axis of rotation, the scale of tangential force can be calculated with the following equation:

$$F_t = \frac{2T}{d} \text{ (Jiang, 2019)} \quad (2)$$

F_t = Tangential force (N), T = Torque (Nmm), d = diameter of gear (mm)

The radial Force (F_r) is also known as the "Separating Force" due to its tendency to separate the driving pinion and the driven gear; this is calculated by:

$$F_r = F_t tan\, \alpha \quad (3)$$

While the normal force (F_n) is calculated by:

$$F_n = \frac{F_t}{\cos \alpha} = \frac{2T}{d cos\, \alpha} \quad (4)$$

2.4 Helical gears

2.4.1 Definition

Helical gears are a type of cylindrical gear that are curved into a helical shape formed by cutters which produce an angle allowing several teeth to mesh simultaneously. Helical gears, while more complex to manufacture, are superior to spur gears in their load carrying capacity, quietness, and smoothness of operation. They do, however, suffer from higher friction and wear than the spur gears.

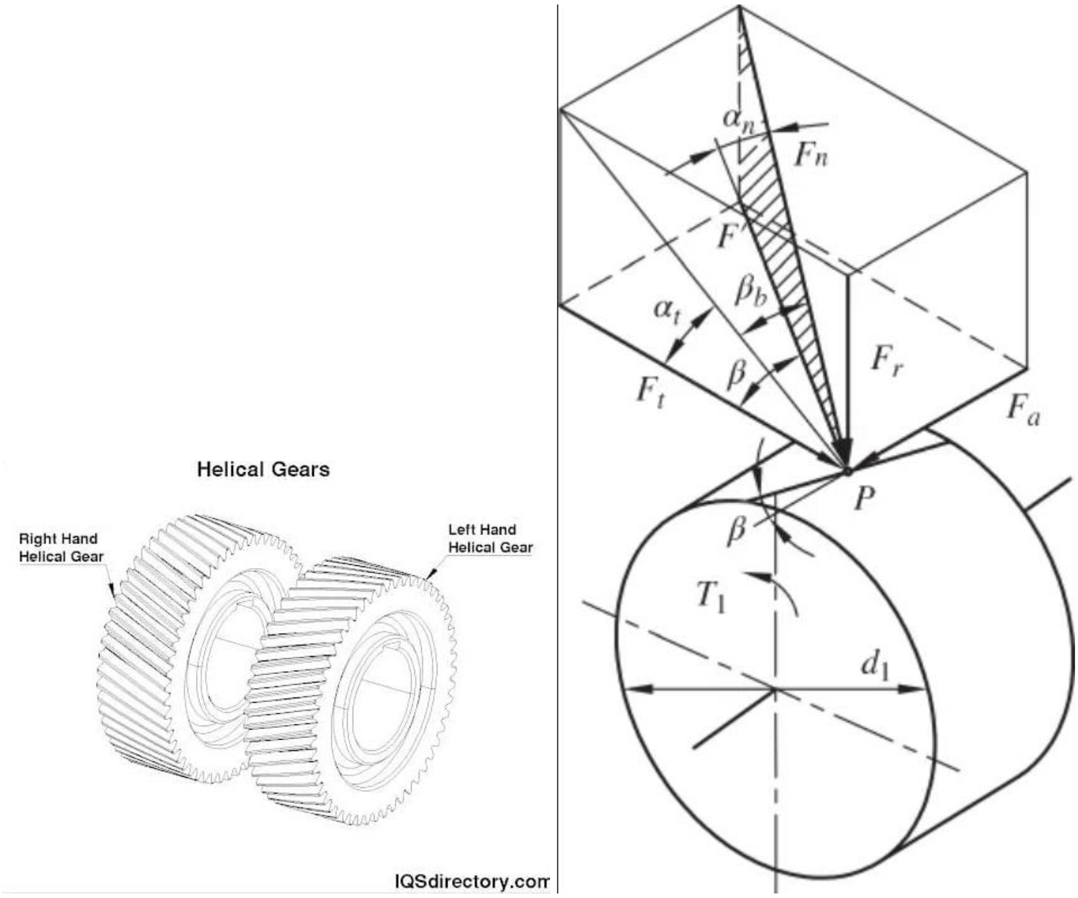


Figure 7*: Helical gear (Industrial Quick Search) and its geometry (Jiang 2019)*

The manufacturing machinery used for producing helical gear is the same as that of the spur gear with the main difference being in the manufacturing method; helical gears are cut at an angle to the axis of the gear and follow a spiral path. This angle, known as the “helix angle” (fig. 8), tends to vary between 5 to 45^o and causes the position of tooth contact with the “mating gear” to *vary at each section* (Keith 2001). Helical gears tend to work in pairs, these pairs must have the same pitch and helix angle and must be opposite “hand” to one another (fig. 7).

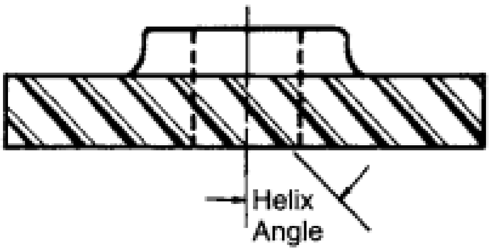


***Figure 8**: Helix angle (Keith, 2001)*

2.4.2 Forces acting on a helical gear's teeth

As can be seen in fig. 7 above, the normal force (F_n) is applied perpendicular to the face of the helical tooth in the normal plane. This falls into three orthogonal components (similar to the spur gear) tangential force (F_t), radial force (F_r) and axial force (F_a).

The tangential force (F_t) is applied on the transverse plane and is at *a tangent to the pitch circle of the helical gear (Jiang 2019).* The tangential force is involved with power transmission and transmits torque from the "driving pinion" to the "driven gear". The equation for deriving the tangential force of a helical gear is as follows:

$$F_t = \frac{2T}{d} \text{ (Jiang, 2019)} \tag{5}$$

The radial force (F_r) acts *towards* the centre of gears and tends to separate the driving pinion and driven gear, contributing to the shaft bending and bearing loads. The F_r can be calculated as follows:

$$F_r = \frac{F_t tan\, \alpha_n}{cos\beta} \tag{6}$$

The axial force (F_a) acts parallel to the axis gear and causes an axial load (also known as "thrust load") that has to be resisted by the bearings. The direction of this axial load can be determined by the "right- or left-hand rule". Once the tangential for (F_t) is known, the axial force (F_a) can be calculated as follows:

$$F_a = F_t \tan\beta \tag{7}$$

One can also, of course, find the normal force (F_n) of the helical gear using the following equation:

$$F_n = \frac{F_t}{\cos\beta cos\alpha_n} = \frac{F_t}{\cos\alpha_t \cos\beta_b} \tag{8}$$

2.5 Bevel gears

2.5.1 Definition

A bevel gear is quite different from the aforementioned spur and helical gears as it's a cone-like shaped gear (fig. 9) with teeth cut in such a manner that two wheels working together have shafts at an angle to each other, usually a right angle; although special bevel gears can be manufactured to operate at any desired shaft angle.

Bevel gears tend to be used in driving a vertical pump with a horizontal driver.

There are two major differences between bevel and spur gears, their shape and the relation of the shafts on which they are mounted. *A bevel gear is conical in shape, while a spur gear is essentially cylindrical…Bevel gears transmit motion between angular or intersecting shafts, while spur gears transmit motion between parallel shafts* (Keith 2001).

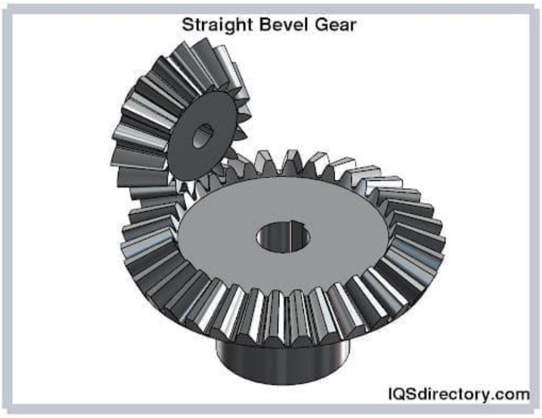


***Figure 9**: Pair of bevel gears (Industrial Quick Search)*

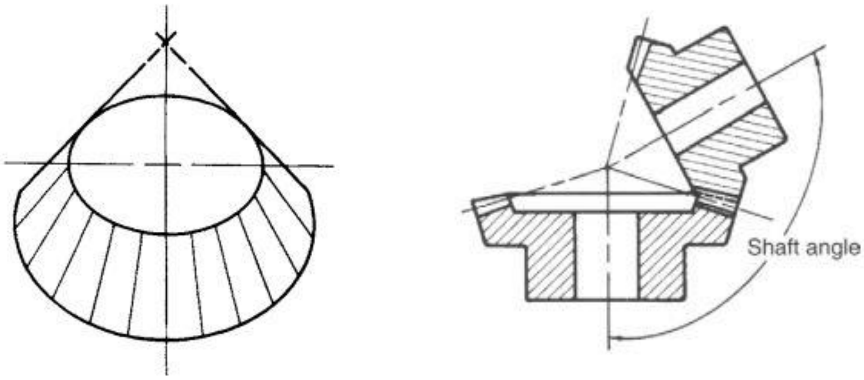


***Figure 10**: Basic cone like shape of a bevel gear and its shaft angle (Keith 2001)*

It is important to note that, since each gear in a bevel gear set must have the same pressure angle, tooth length and diametrical pitch, they must be manufactured and distributed as mated pairs only. Furthermore, since there is usually no room to support bevel gears at both end (due to intersecting shafts) one or both gears "overhang" their supporting shafts (fig. 10); this tends to be referred to as an "overhung load". The overhung load may cause shaft deflection and gear misalignment, leading to poor tooth contact and accelerated wear.
The general shaft angle is 90º (Keith, 2001) but this isn't always the case (fig. 10), as it is possible to produce bevel gears with custom angles. In terms of the angles available for purchase, bevel gears, like spur gears, are available in pressure angles of 14,5ò and 20º; though special orders can also be made.

2.5.2 Forces acting on a straight bevel gear's teeth

The loads applied on the bevel gear is nonuniform and significantly greater at the large end; according to Jiang 2019 this is due to the bevel gear teeth being "tapped in both tooth thickness and height".

The normal force (F_n) can be assumed to be acting at the midpoint of face width of a bevel gear teeth (fig. 11).

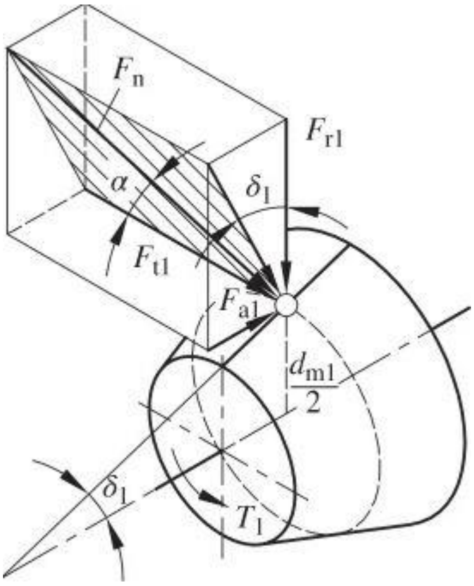


***Figure 11**: Bevel gear force analysis (Jiang, 2019)*

The normal force (F_n) on the pinion, can be divided into three, usually perpendicular, components: a tangential force (F_t), a radial force (F_r) and an axial force (F_a) (similar to the spur and helical gear). The tangential force (F_t) acts, as the name says, tangentially to the pitch cone, and is the force that will produce torque on the pinion as well as the gear. This tangential force can be calculated as follows:

$$F_{t1} = \frac{2T_1}{d_{m1}} = F_{t2} \quad (9)$$

The radial force (F_r) affects the centre of the pinion and is perpendicular to its axis; hence the equation for calculating the radial force is:

$$F_{r1} = F_{t1} tan\, \alpha\, sin\, \delta_1 = F_{r2} \quad (10)$$

Finally, the normal force (F_n) can be calculated as follows:

$$F_n = \frac{F_{t1}}{\cos \alpha} \quad (11)$$

2.6 Gear manufacturing processes

When it comes to advanced gear manufacturing processes the classifications generally fall into four main categories: subtractive (material removal process), additive processes, deforming processes and hybrid processes.

As there are a myriad of different manufacturing methods that fall into each category the thesis shall focus on just one manufacturing method per criteria; these being:

- Laser Machining for subtractive processes.

- Additive Layer Manufacturing for additive processes.
- Hot Embossing for deforming processes.
- Lithographie, Galvanoformung and Abformung (Lithography, electroplating and Molding) for hybrid processes.

2.6.1 Laser machining

With an excellent balance between speed, accuracy and cost, laser machining utilises the high energy density of a laser beam to quickly and smoothly ablate (or vaporise) materials regardless of their thermal, physical or chemical properties. The means in which laser beams produce products such as gears is rather straight forward; with the proper instructions inputted into the laser, it fires a concentrated laser beam at the metal from which the gear would be formed. In their book “Advances in gear manufacturing. Advanced gear manufacturing and finishing” Kapil Gupta et al. explained the workings of the laser beam as follows:

The laser beam, generated in the laser source, is directed towards the cutting head or nozzle by a set of mirrors, where it is focused by a lens onto a localised region of the workpiece (gear blank). The intense laser beam quickly heats up the gear material to beyond its melting temperature. The assisting gas, also referred to as the cutting gas, protects and cools the focusing lens while also removing the molten material from the kerf.

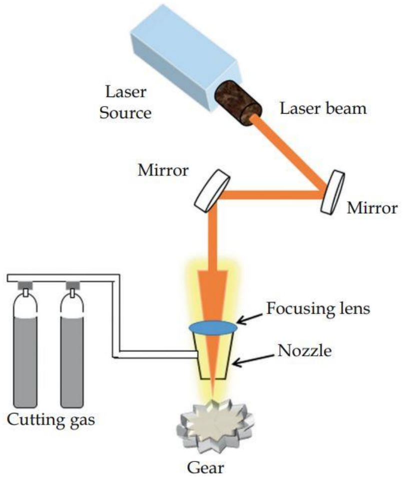


Figure 12*: Laser machining, a schematic representation (Gupta et al, 2017)*

Typically, the type of lasers used for cutting and producing gears are carbon dioxide lasers, excimer lasers and solid-state lasers such as “Nd:YAG” and “Yb:YAG”.

2.6.2 Additive Layer Manufacturing

ALM [Additive Layer Manufacturing] *is an advanced manufacturing technology which uses a bottom-up approach to manufacturing a complex part or even an assembly from its CAD model by layered deposition of the material.* (Gupta et al., 2017).

ALM is, simply put, 3D printing of a product from a CAD model using a 3D printer.

ALM can be used to manufacture new net shaped or near net-shaped complex component or assemblies; and/or it can be used to add delicate features to an existing component. There are many advantages to ALM, including (Gupta et al, 2017):

- It is energy and material sufficient due to large reduction of scraps.
- Generally faster than conventional manufacturing methods such as subtractive methods.
- No requirements for detailed working drawings of the component or parts.
- Eliminates the need to procure materials in specific size and shape.
- Eliminates the need for the production planning being specific to a part, machine or manpower availability.
- No need for intermittent quality checks.
- Limits human intervention errors.

ALM falls into three categories according to the state of the raw material used (Liquid, solid or powder):

Table 1: ALM Categories (Gupta et al., 2017)

ALM type:	**Raw material:**	**Function:**	**Examples:**
Liquid-based ALM processes	Liquid state material	Liquid state material is cured by the 3D printer	- SLA apparatus - Solid ground curing - Solid creation system - Solid object ultraviolet (UV) laser plotter
Solid-based ALM processes	Raw material in the form of wire, pellet, laminates or rolls	Solid raw material is inserted into the 3D printer. The solid is melted and ejected from a nozzle which forms the shape of the desired product. When finished, the product is cooled before the user can remove it.	- FDM - Laminated object manufacturing - Multi-jet modelling - Selective adhesive and hot presses - Paper lamination technology - RP system - Laser metal wire deposition - And more

Powder-based ALM processes	Powder	The functions depend heavily on the type of powder 3D printing used. Nevertheless, there are two main powder printing processes: powder bed fusion and binder jetting. With powder bed fusion, 3D printers either sinter or melt powder particles with laser into the desired product layer by layer, while a recoating blade applies more powder per new layer. Binder jetting, uses a print head that deposits a liquid bonding agent on to the powder print bed which would bind the powder particles together, forming each layer of the desired object. A new layer of powder is the added and the process is repeated layer by layer.	- Fused deposition of ceramics - Ballistic Particle manufacturing. - Three-dimensional printing (3DP). - Multiphase jet solidification - Direct Shell production casting - SLS - Direct metal laser sintering

The basic steps required for gear manufacturing (and other products) using ALM commences with the creation of a 3D CAD Model using any 3D modelling software (e.g. SolidWorks, 3DS Max etc) followed by the creation of an STL file from the 3D CAD model. The STL file would convert the CAD model into 3D meshes of triangular elements. After this, the CAD model is “sliced” i.e., intersecting the CAD model with a plane as to determine 2D contours and to define layers.

With the CAD model converted into a series of layers, and with a file containing instructions tailored for the specific ALM machine generated, the gear is manufactured according to the CNC part program. Depending on the type of 3D printer being used, and depending on the settings the user selected, some post-manufacturing cleaning might be necessary such as removal of support material, finishing etc.

2.6.3 Hot embossing

Hot embossing is a fabrication technology involving the use of thermal energy and pressure to impress a master mould into a polymer substrate in order to transfer the inverse of the structures on to the surface of the opposing polymer substrate. Heat embossing is used greatly in the manufacturing of precise micro or nanofeatures across a small area of a substate. *Typical applications include thermoplastics at an elevated temperature and approximately 10 bar pressures…Hot embossing involves pressing the workpiece material into a master die or mold to replicate the desired mold geometry.* (Gupta et al., 2017)

The principle of hot embossing (fig. 13) is as follows:

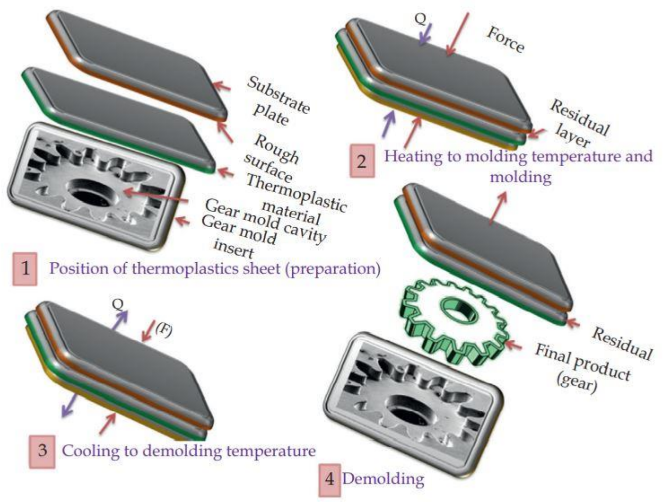


Figure 13*: Hot embossing process (Gupta et al. 2017)*

1. The first step is the "Positioning of the thermoplastic sheet", in which a micro-mould that corresponds to the gear (that will be manufactured) is placed on top of the polymer substrate as to obtain a stack which is placed on a lower heating plate containing cooling channels. "Oil with high heat capacity" is then circulated within the cooling channels in order to ensure isothermal heating and cooling of the mould and the polymer substrate.
2. In the next step, "heating to the moulding temperature and moulding", the lower heating plate is displaced vertically to "heat up the stack" while keeping an appropriate "Pneumatic or Hydraulic" pressure. To ensure that the reproduction of the mould to the substrate is effective, the mould and substrate are heated above the glass transition temperature of the substrate material; softening the substrate material and reducing the force required to fill all the cavities of the mould.
3. With the heating done the embossed (or moulded gear) is cooled to the demoulding temperature (to solidify) by cooling the plates while the pressure constant is still maintained.
4. Finally, the now embossed gear is removed from the mould.

The advantage to hot embossing includes (Gupta et al., 2017):

- It’s the best cost-effective reproduction process for “high aspect ratio micro-gears” due to its high dimensional accuracy.
- It can reproduce a large selection of microfeatures such as micro-gears on the substrate with the usage of a single master die.
- Provides mould life due to being highly reusable, due to low wear.

The limitation of hot embossing includes:

- Used mainly for thermoplastics only, thus it has a smaller use case.
- Difficult to attain a high embossing pressure.
- Tool and die making as well as the ancillary equipment used in this technique are expensive and complicated.

2.6.4 Lithography, Electroplating and Moulding

Lithography, Electroplating and Moulding, known also as LIGA (Lithographie, Galvanoformung und Abformung), is a production method used to create high aspect-ratio microstructures by deep X-ray lithography. An important material for the process is the substrate which, in this case, would be an x-ray sensitive photoresist material upon which the gear shaped would be developed after it is struck by x-ray. The desired properties of this substrate are as follows:

- It must be thermally stable up to elevated temperatures.
- Must have excellent adhesive properties during the electroplating process.
- Must have dry and wet etching resistant.
- The unexposed “resist” material, during the development process, must be insoluble.

The photoresist substrate tends to be made from materials such as Polymethylmethacrylate (PMMA), Polyvinylidene fluoride, Polycarbonate, Polysulfones, Epoxy phenol resin, Plexiglass and Polyether ketones. It is important for these materials to be prepared so that they can facilitate any electrodeposition in the prepared mould of photoresist, this can be done by removing foreign material particles from its top surface and placing on base material capable of being conducting or electrically conductive coated insulator. Great base materials include, titanium, nickel, austenitic steels or “copper plated with gold and silicon wafers with thin titanium layers” (Gupta et al., 2017).

The process is described as follows (Fig.14):

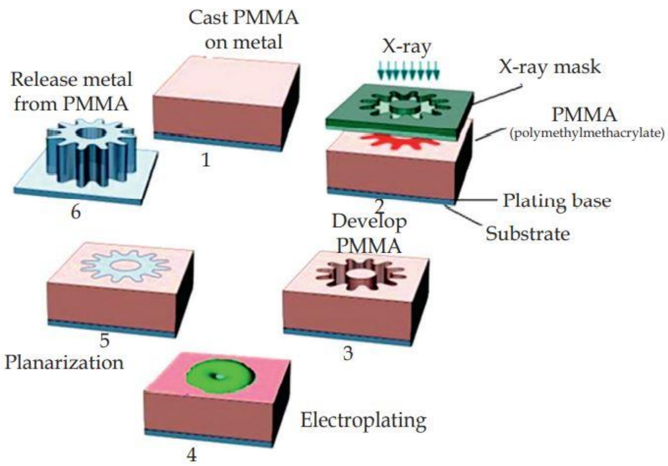


Figure 14: *LIGA gear manufacturing steps (Gupta et al. 2017)*

1. Before beginning the process, a mask with the gear shape is prepared using a thin film made from gold on beryllium. This would ensure that the x-ray mask transmits the appropriate volume of x-rays to the photoresistant material only.
2. With the preparations made, a deep x-ray lithography (DXL) is then used to process and develop the gear shape onto the x ray sensitive photoresist material.
3. Next step is the “transfer of the pattern by X-ray exposure of the substrate”, where the substrate is exposed to “parallel x-rays of short wavelength” (Gupta et al. 2017) through the openings in the X-ray mask. Since the x-ray fires rays of short wavelength, it can provide accuracies of 0,2μm and aspect ratios of 100, which is important as the high-resolution exposure of high aspect ratios provide sharp, deep and thin cavities of the desired gear shape.
4. Next, the exposed photoresist material (or possibly unexposed, depending on the type of photoresist material) is removed chemically, showing the gear geometry in the form of an accurate mould cavity containing the gear outline.
5. The photoresistant mould is then filled through an electrodeposition process where it’s placed into an electrodeposition bath. Here the gear material would be deposited from the bottom up.
6. Next the excess electrolytically deposited material is removed from the top surface of the mould which would result in a flat surface.
7. Finally, the surrounding photoresist material is removed from the manufactured gear.

LIGA is an important process which can be used to, manufacture micro-gears with complex geometries and shapes for many industrial, and even scientific, usages. Yet it too has advantages and limitations:

- The LIGA process can be used to manufacture both metallic and plastic micro-gears with high precision and high aspect ratio; with dimensional accuracy of less than 1μm and nanometre scale surface finishes.
- Offers enhanced flexibility in geometry.
- Highly suitable for mass production.

The following are its limitations:

- Possible radiation threat to operator(s) due to requirement for high energy X-rays.
- Complicated multistep process.
- The excessive cost of the equipments, especially due to their one-time-use nature in the case of the substrate.

2.7 Planetary gear

A Planetary gear, also known as "Epicyclic gear" or "Planetary gearset", is a system consisting of two gears mounted in such a way that the centre of one gear revolves around the centre of the others. The gear consists of a "Sun" gear (at the centre) with the "Planet gears" revolving around the "Sun" gear while being supported by a "Carrier" and a "Ring/Internal gear". (Forsthoffer, 2022)

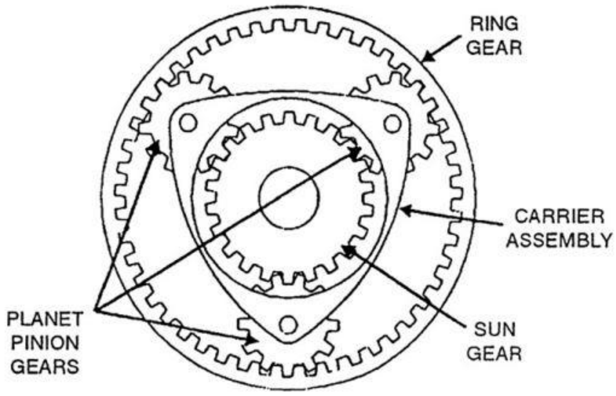


Figure 15: *Planetary gear (Forsthoffer, 2022)*

Planetary gears are widely used in engineering (i.e. in automotives) and have the advantage of allowing both the input and output axes to be concentric, which provides for a more compact gear arrangement. Including Automotives (for their transmissions), Planetary gears are also used in aircrafts proppeller engine drives, truck transmission, power generation units as well as in some critical equipment drives (i.e. pump and compressor). (Forsthoffer, 2022)

As can be inferred from the gears name, Planetary gears are designed to mimic the formations of the solar system. The planetary gears each turn on their axis whilst rotating around the Sun gear; in turn these Planet gears mesh with the Ring gear while their pinion bearings are being held by the Carrier assembly. Should power be applied to any one of the members, the entire assembly rotates; conversely, if one of the other members is restrained, the remaining members will provide the output. If none of the members are restrained, the assembly will be in a neutral situation. (Forsthoffer, 2022)

As great as they are, Planetary gears do have some disadvantages as well. Planetary gears are extremely complex in design due to them having multiple gears and bearings, this makes them more difficult to monitor than other gears.

Due to this complexity, planetary gears are maintenance intensive and have higher "mean time to repair (MTTR)" in comparison to other gears (i.e., parallel shift gears). (Forsthoffer, 2022)

2.8 SolidWorks

The design, assembly and analysis processes of the Planetary gear will take place in SolidWorks. SolidWorks is a solid modelling CAD (computer aided design) and CAE (computer aided engineering) software by Dassault systems.

As mentioned, it is within SolidWorks that the planetary gear will be designed and then assembled. Following the assembly process the gear will undergo 2 forms of FEM (Finite Element Method) analyses from which conclusive results will be drawn from. These are contact analyses and a torque simulation.

2.9 Methods of analysing the Planetary gear

2.9.1 Contact Analysis

Between various components within a mechanical system exists a state of static or dynamic contact such as meshing gears, forming processes and indentation simulations; to this end, it is imperative to study and analyses the area of contact between these countless mechanisms to ensure that the machine can run smoothly. This is where contact analysis comes in handy. Contact analysis is a form of FEM/FEA analysis that investigates the contact point as well as the contact force at the contact points such as the contact pressure and frictional force (Nagaraj et al., 2020).

This has become increasingly important in the recent years with the increased usage of composite laminated materials wherein impact can cause localised damage and delamination, which tend to lead to severe reduction in the structural mechanical properties (Nagaraj et al., 2020).

Contact analysis can, and will, be used on the planetary gear assembly using SolidWorks.

2.9.2 Torque Analysis

Torque is a measure of the force that rotates an object about an axis. Torque analysis is therefore a series of tests used in order to determine the magnitude of force the sample, in this case the Planetary gear, can reliably handle the normal functions of a Planetary gear. Planetary gears are used as speed reducers (or increases in some cases) used to slow down (or speed up) motors and increase torque. They are, therefore, expected to be able to handle a high amount of torque (with some companies claiming that theirs can handle up to 113000 Nm of torque as a part of a shaft output gear ['Planetary Gears', 2019]). The Planetary gear is a hypothetical example and will not be expected to handle a high magnitude of torque.

3 METHOD

As an example of a material element this portion of the thesis will focus on the modelling and analysis of a custom planetary gear as a theoretical case study. The aim of the method is to show the simplicity in the design of a planetary gear as well as being a visual example of a working material element and its design process. The planetary gear, as mentioned before, is composed of Carrier, Ring, Sun and Planet gears. In this section focus is given to the 3D modelling process as well as the analysis techniques used to create and analyse the Planetary gear.

3.1 Calculations

For the Planetary gear to work smoothly with little to no teeth interferences, the parts making up the Planetary gear must satisfy the three conditions outlined and their corresponding equations (*Gear Systems | KHK Gear Manufacturer*):

Condition one: the ratio of the number of teeth of the Ring gear to that of the Sun and Planet gears must match the following equation.

$$Z_R = Z_s + 2Z_p \tag{12}$$

Z_R= number of Ring gear teeth, Zs= No. of Sun gear teeth, Z_p= no. of Planet gear teeth

Condition two: The gears must be capable of working together, with adjacent gears being unable to interfere with one another.

$$Z_P + 2 < (Z_s + Z_P)\sin\left(\frac{180}{N}\right) \tag{13}$$

N = Number of planetary gears

Condition three: The planet gears must be spaced equally around the sun gear.

$$\frac{(Z_S + Z_R)}{N} = d \tag{14}$$

d = distance (mm).

The equation has no units but as it denotes a distance between planet and sun gears, the unit of mm will be given. Recall, this equation ensures that the planet gears are evenly spaced around the sun gear.

It's important to note that the number of Sun and Planet gear teeth, which would give the number of Ring gear teeth, can be arbitrary so long as they adhere to both equations 12 and 13.

Using the three equations the following calculations were made:

The Number of Ring gear was chosen to be 60. Generally, the more teeth the smoother the operation of the planetary gear; 60 (in this case) was chosen arbitrarily.

This is fine so long as the number of teeth chosen for the Ring gear (Z_r), as well as the numbers chosen for Z_s and Z_p (by e.g. trial-and-error method) satisfy both equations 12 and 13.

The numbers that satisfy these equations were Z_s = 16 and Z_p = 22 as can be seen below:

$$16 + 22 \times 2 = 60$$

And

$$22 + 2 \ < (16 + 22) \sin\left(\frac{180}{4}\right)$$
$$=> 24 \ < 26{,}87$$

As can be seen the set of teeth chosen for the three gears satisfy equation 13 and therefore can mesh together without too much interference.

The calculation for condition three would set a good distance between the planet gear centre and the sun gear centre.

$$\frac{16 + 60}{4} = 19mm$$

In this case a distance of 19 mm is deemed best.

With the calculations complete, the design process began.

3.2 Design process

First was the internal Spur gear, which would work as the Ring gear. This was not made from scratch, rather taken from the SolidWorks design library just as one would purchase an internal spur gear for usage rather than build a new one. The gear was taken from the ISO, Power transmissions, Gears (Appendix 1). The gear was designed using the internal spur gear obtained from the SolidWorks design library, which, when brought into the design space, had its number of teeth modified to 60 (eq. 12). The gear was then saved. The configurations can be seen in Table 2.

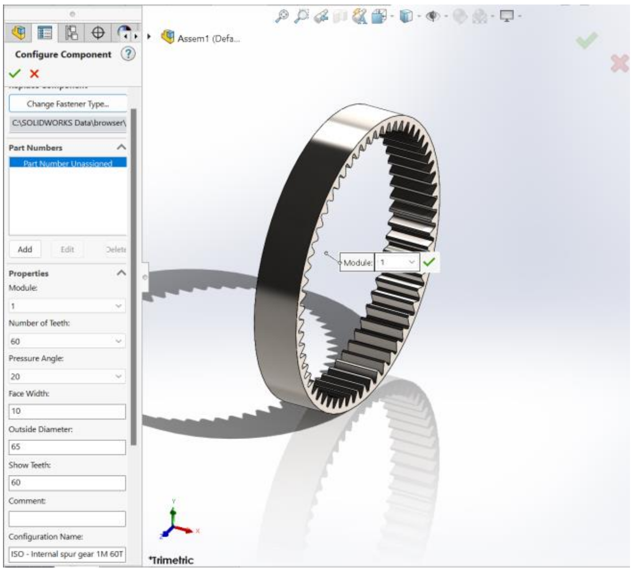


Figure 16: *Internal spur gear configuration.*

Table 2: Carrier gear parameters

Parameters	Values
Module	1
Number of Teeth	60
Pressure Angle	20 º
Face Width (mm)	10
Outside Diameter (mm)	65

With the carrier gear complete, the next step was to create a Planet gear. For this, an external Spur gear was taken from the design library (Appendix 1) and had its configuration set as shown in Table 3. Module indicates the relation between the number of teeth and the gears working diameter, a module 1 means that a 60 teeth gear would have a diameter of 60mm, module 2 would, for 60 teeth gear, be 120 mm diameter. For the custom Planetary gear, module 1 (i.e. gear diameter of 60 mm) would suffice.

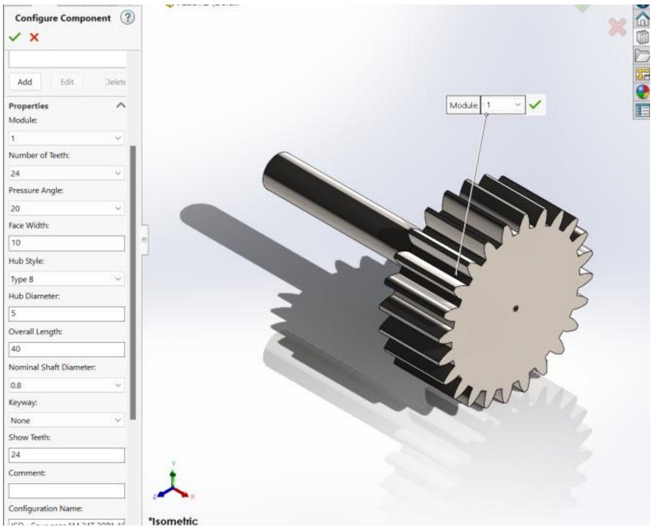


Figure 17: *planet gear configuration.*

Table 3: Planet gear parameters

Parameters	Values
Module	1
Number of teeth	24
Pressure angle	20 °
Face width (mm)	10
Hub diameter (mm)	5
Overall length (mm)	40
Nominal shaft diameter (mm)	0,8

A small extrusion of 1mm was cut into the tip of the planet gear to aid in the mating process between the planet gears and their respective ball bearing as shown later. Soon after, the gear was filleted. Finally, the hole in the centre of the gear was covered up by drawing a circle and extrude cutting it through the model to the other side.

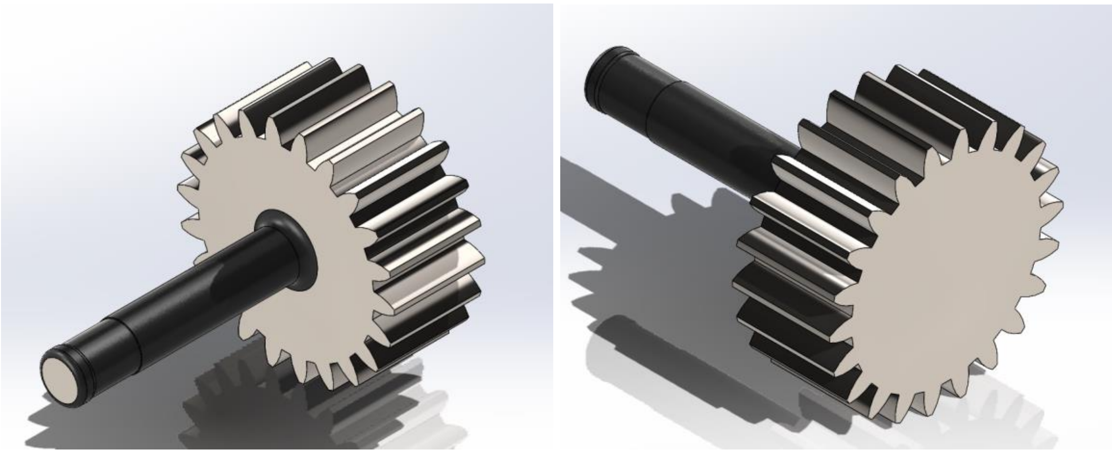


Figure 18*: Complete Planet gear.*

The chosen material for the Planet gears, just as with all the other gears, was the Gray Cast Iron. This is because, according to Pardhiv et al. (2019) nodular graphite cast Iron is the most ideal material for planetary gear parts but as this is not in SolidWorks the closest material was used, hence why Gray Cast iron was chosen. This is not to say that they are the same, as nodular cast iron has higher strength and toughness than gray cast iron; but it will have to do as a substitute.

With a planet gear created, another external Spur gear was taken from the design library to function as the Sun gear. The configurations chosen can be seen in fig 18. The Sun gear's configurations (Table 4) were identical to the planet gears with the only difference being that the number of teeth was 16.

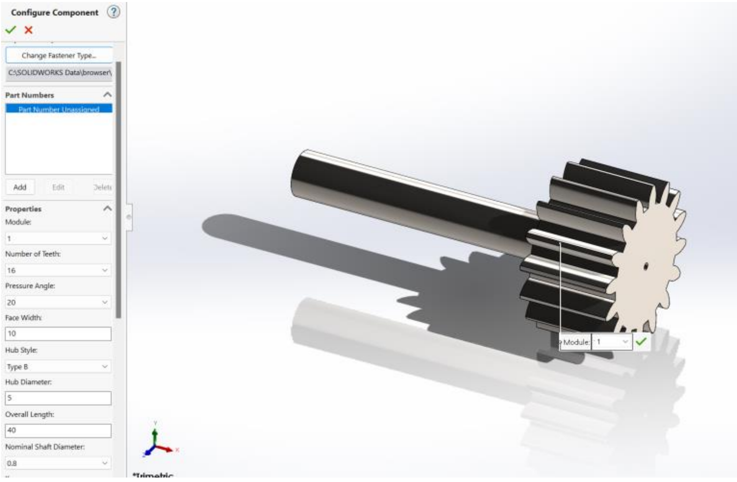


***Figure 19**: Sun gear.*

Table 4: Sun gear parameters

Parameters	Values
Module	1
Number of teeth	16
Pressure angle	20 º
Face width (mm)	10
Hub diameter (mm)	5
Overall length (mm)	40
Nominal shaft diameter (mm)	0,8

With the initial configurations complete, the Sun gear would undergo modifications to make it functional to the Planetary gear. First, a 20 by 1,5mm square is drawn and revolved near the tip of the gear. This would work as a rotation handle.

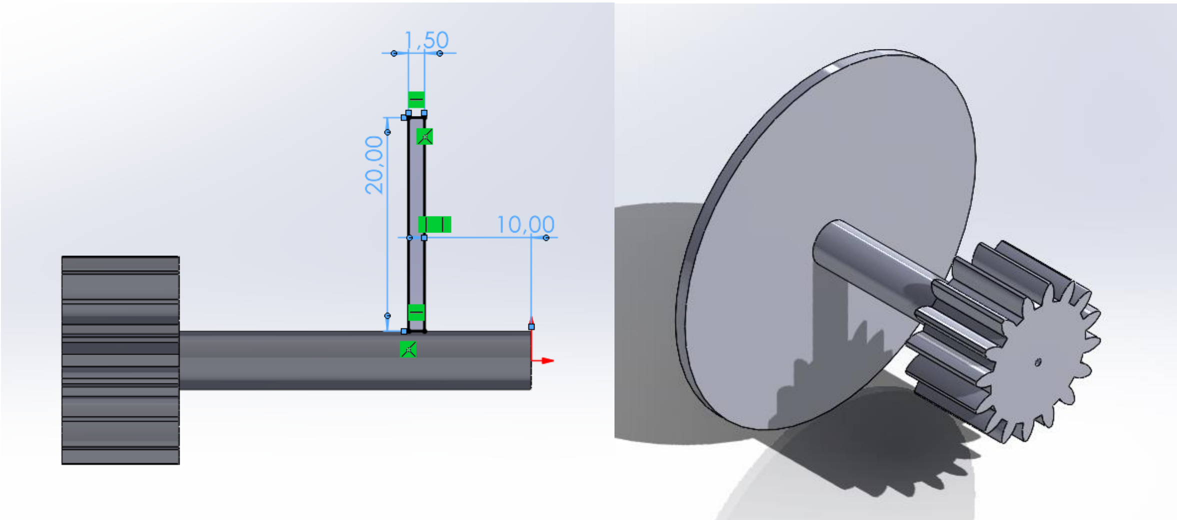


***Figure 20**: Sun gear handle.*

The very tip of the gear is then chamfered while the handle is smoothened with a fillet.

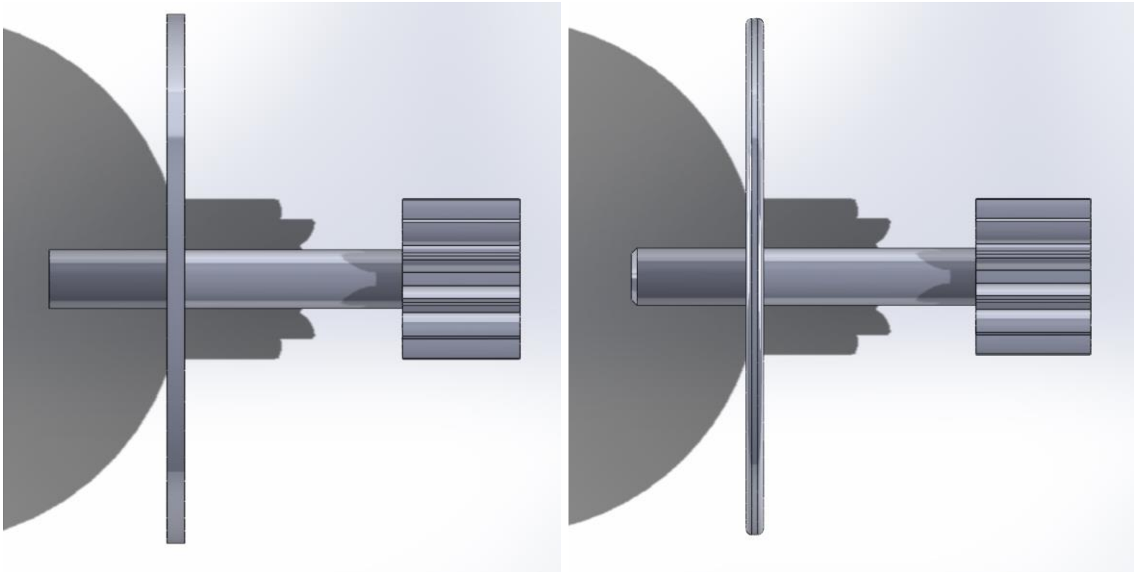
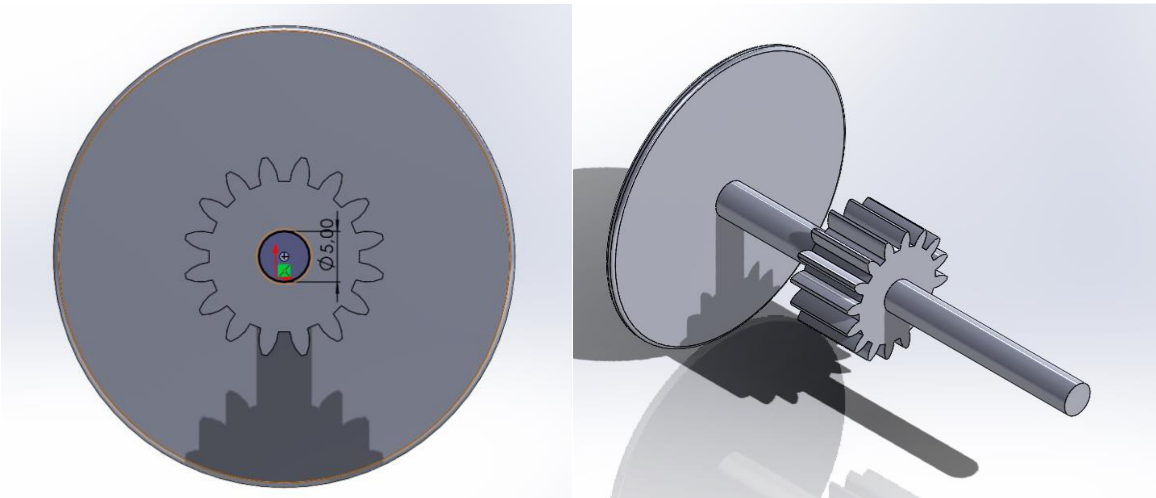


Figure 21*: Chamfer and fillet.*

Next step was to create an extruded extension which would be inserted into the carrier assembly to hold it in place. First a circle was drawn at the front and printed on to the surface using the “split line” command; with this done a circle a circle of d = 5mm was drawn at the centre of the split line and extruded by 35 mm.



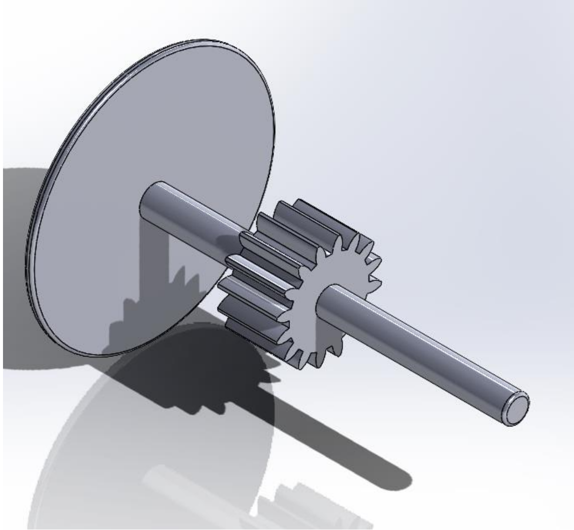


Figure 22: *Extruded extension.*

The material was set to Gray Cast Iron and the main body of the sun gear was given a metallic gold finish to make it appear more like a “Sun”. With that, the Sun gear was complete.

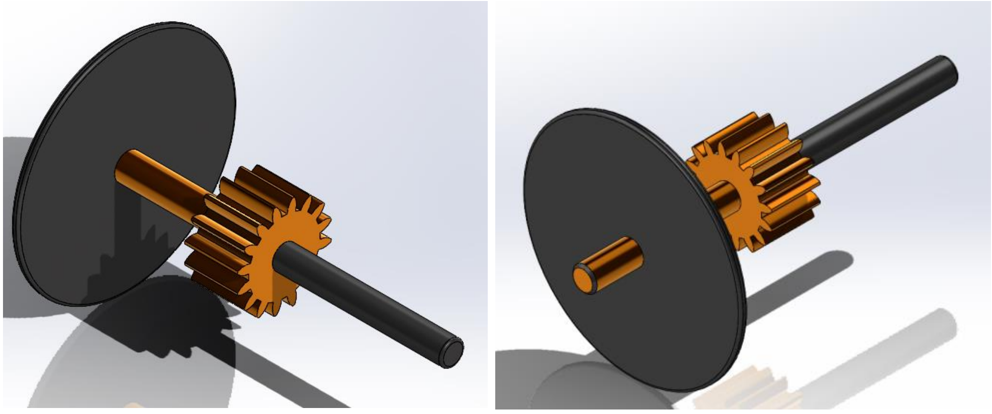


Figure 23: *Material and appearance.*

The final piece of the Planetary gear is the Carrier assembly and contains four ball bearings for each hole.

The Carrier gear was drawn by first making 4 circles of 9 mm enclosed within 4 semi circles of 15 mm all joined together with straight lines to make what looks like a “plus” symbol (fig. 23). The distance between the centre hole of 5mm and the four 9 mm circles is 19 mm as calculated is eq. 14. This drawing was then extruded by 3,5 mm.

Next the 5 mm hole in the centre was extrude cut through the part.

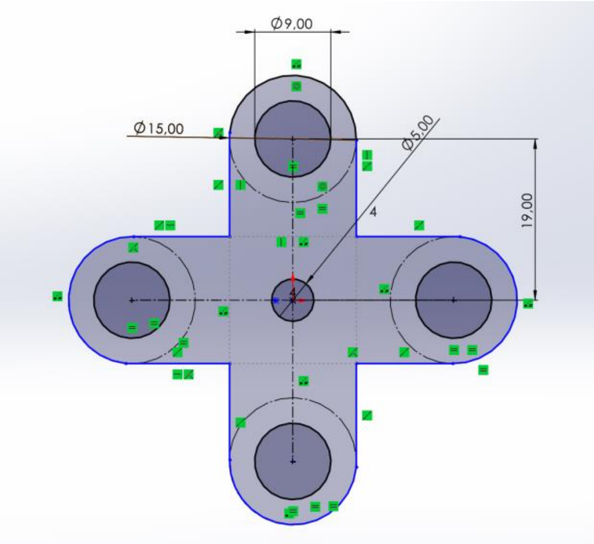


Figure 24: *Drawing and extrusion of Carrier gear.*

Then, the circle at the very centre was extruded cut separately.

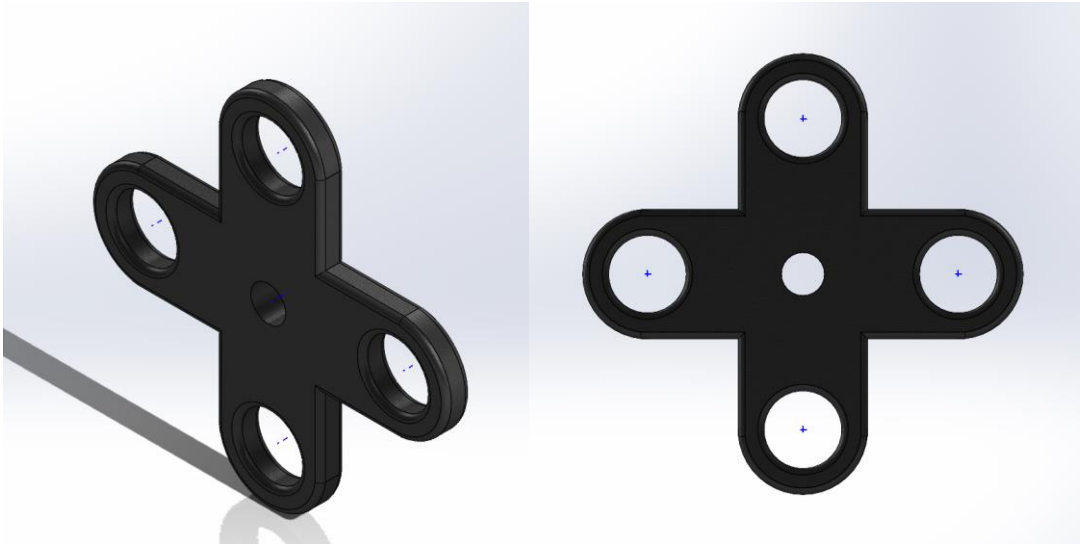


Figure 25*: Extrude cut centre circle.*

The Carrier gear was then opened as an assembly and had angular contact ball bearings from the design library added (appendix. 2). With the bearings mated to each hole of the carrier gear, the gear was complete.

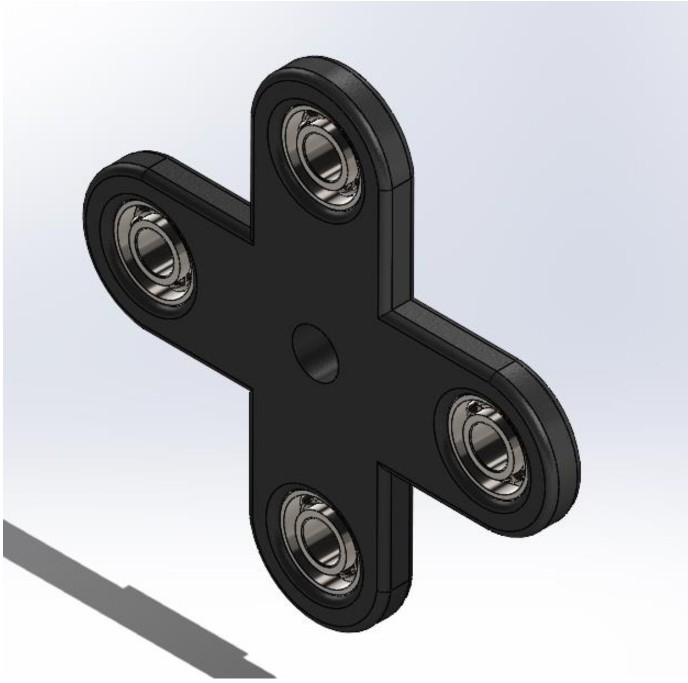


Figure 26: *Carrier with contact ball bearings.*

3.3 Assembly

In the assembly, the Ring gear was brought in first and had the Sun gear mated to it with a concentric mating. Next, four plant gears were mated to both the ring and Sun gears with concentric mates before being aligned.

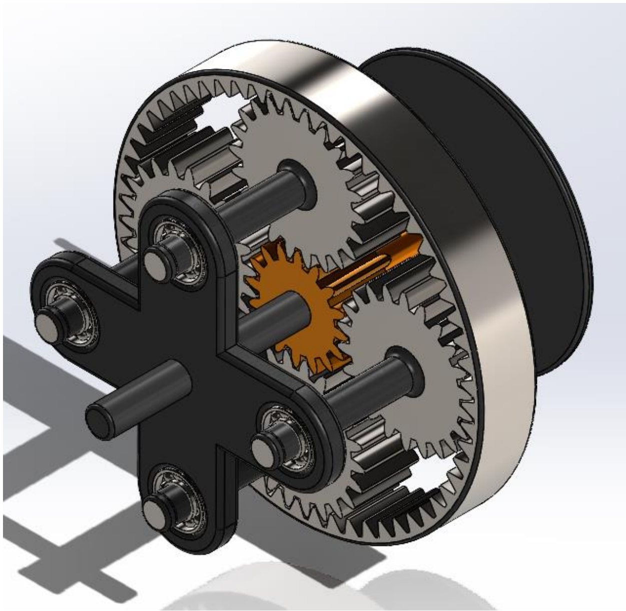


Figure 27: *Fully assembled Planetary gear.*

The teeth of the Planetary gears were then mated to the Ring gear teeth. This was done in the "mechanical" section of the Mates, here a ridge face between two teeth on both the Ring and a Planetary gear were selected, then (on the property manager) the "Gear" icon was selected and, in the "Ratio" segment, the number of teeth on both gears (60 for Ring and 22 for Planet) were inserted.

This was repeated for all the planet gears.

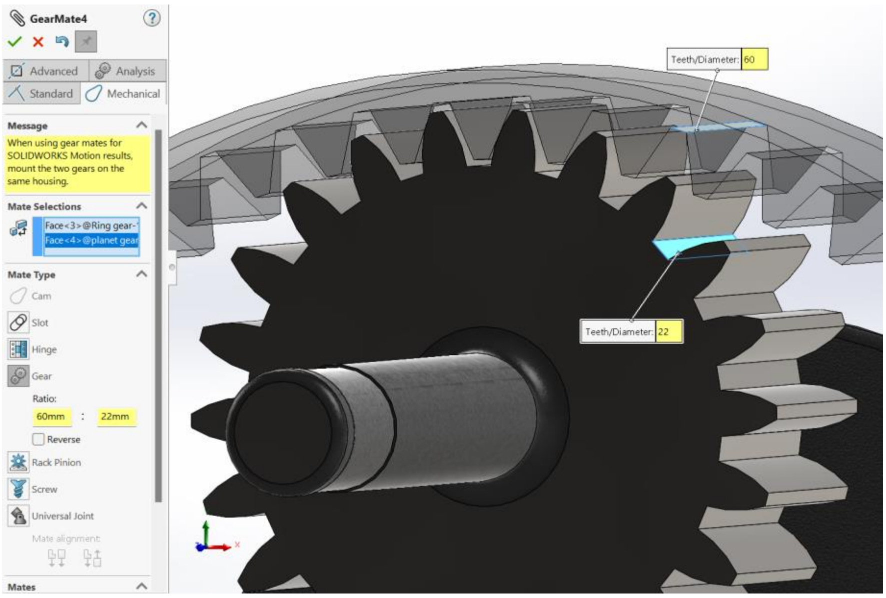


Figure 28: *Gear mate between Ring gear and Planet gears.*

The same was done between the Sun gear and all the Planet gears. In this case, the numbers written under "ratio" were 16 for the Sun gear (as it contains 16 teeth) and 22 for all the planet gears.

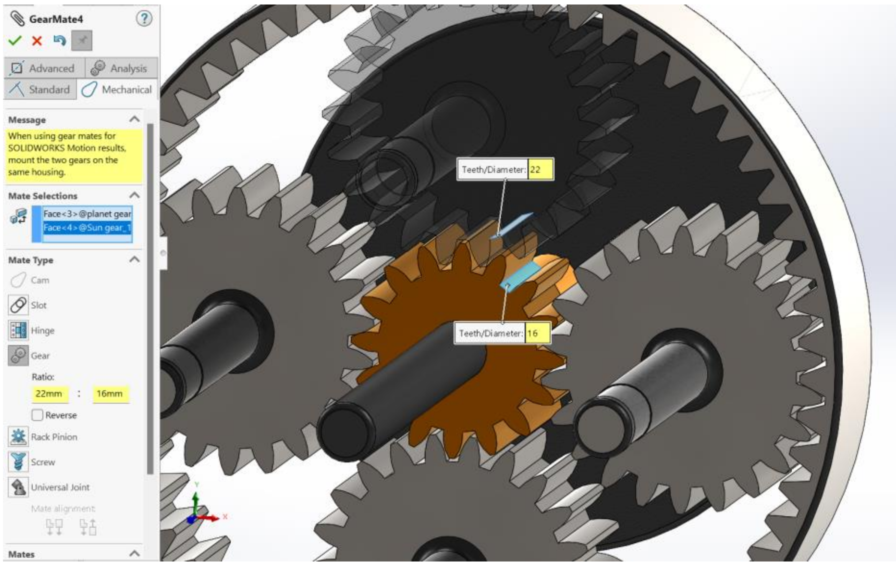


Figure 29: *Gear mate between Sun gear and Planet gears.*

Next the carrier gear was brought into the assembly and was mated to each of the Planetary gears with concentric and coincident mates. With that, the assembly was complete.

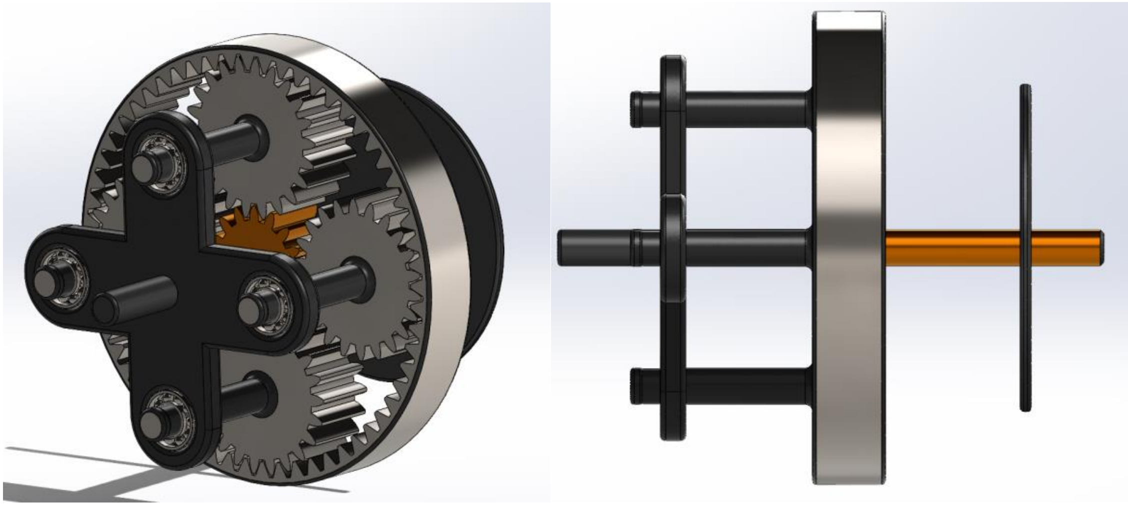


Figure 30*: Fully assembled planetary gear.*

3.4 FEM Analyses

The FEM analyses conducted on the Planetary gear were Contact analyses and a torque analysis. The contact analyses focused on the interaction and interferences between the meshing teeth of the Ring and Planet gear (Ring-Planet) and the Sun and Planet gears (Sun-Gear). The relation between the meshes were created using mathematical calculations, thus these analyses would not only help to show whether the gear teeth mesh smoothly and without interferences but would also prove that the calculations made were correct. The Torque analysis tests the capability of the Planetary gear. Planetary gears are used as speed reducers (or increases in some cases) used to slow down (or speed up) motors and increase torque. This test would thus analyse how much torque the Planetary gear can handle and whether it's capable of functioning as expected of a Planetary gear.

3.4.1 Contact analysis 1: Ring – Planet teeth

The focus of this analysis is to verify the level of interference between the teeth of the Ring and the Planet gears, for this reason all other parts have been supressed with only one Planet and the Ring gear being left unsuppressed.

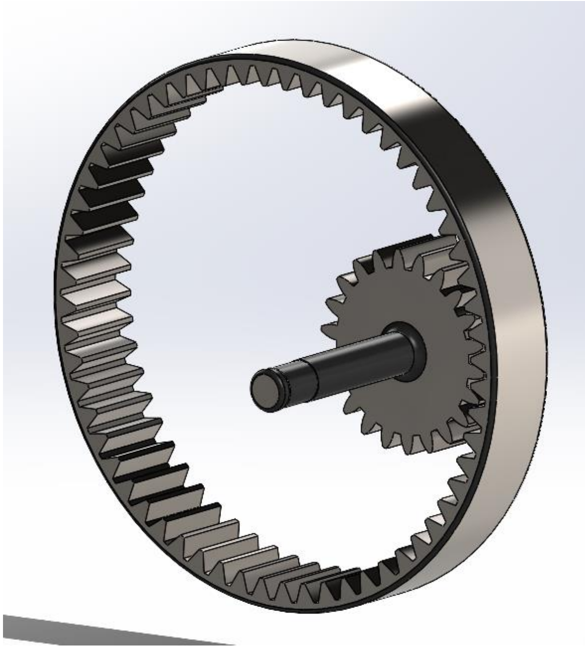


Figure 31*: Ring - Planet gear teeth contact analysis.*

The analysis commenced. Just as with all the other analyses, to start a study the “new study” icon is selected and, under the “General simulations” tab, the “Static” option is chosen. With the study having commenced, the parts materials are first defined (though this tends to be done automatically). For the “connections”, the component interaction option was selected and within it both models were chosen.

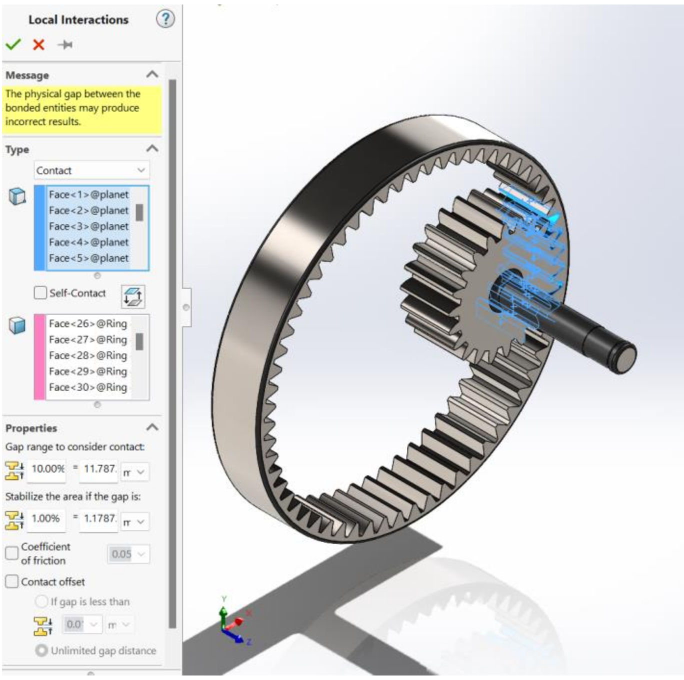


Figure 32: *Local interaction.*

Cylindrical fixtures were also placed onto both models in order to hold certain faces in place. The cylindrical fixtures were placed on the external face of the Ring gear and the internal hole of the Planet gear.

For the Ring gear the “Translations” were all left at 0 but for the Planet gear all the “Translations” except for the “Circumferential” were set to 0; with the circumferential being set to 0,0174 rad. The reason for this is because unlike the Ring gear, the Planet gear is expected to rotate while it is functioning; in this case it was necessary to make sure that the fixture placed on the Planet gear would fix all motions except for rotation.

A good way to do this was to assign the Planet gear a small but noticeable rotation that would show results after the analysis; the amount chosen was a rotation of 0,1^{o} which amounts to approx. 0,0174 rad.

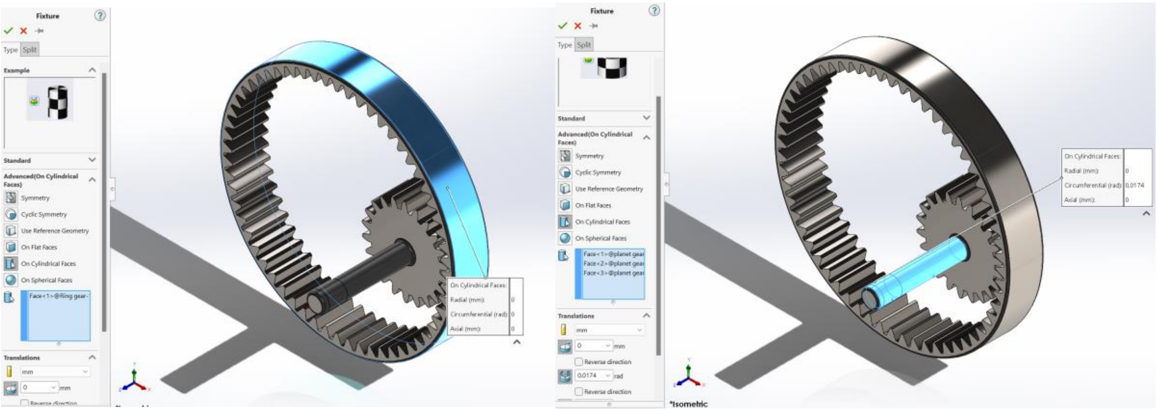


Figure 33: *Fixture.*

A mesh is then created, and the study run.

3.4.2 Contact Analysis 2: Planet – Sun gear teeth

A study was started in the same way as the previous contact analysis. Here though, the focus was on the interaction between the teeth of the Sun gear and a Planet gear.

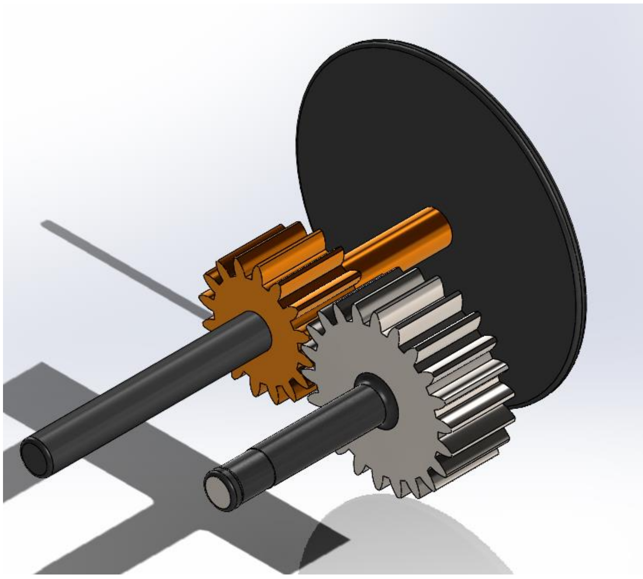


Figure 34: *Planet - Sun gear teeth contact analysis.*

For the “Connections” a “local Interaction” was chosen with the interactions being the teeth from both gears that were interacting (fig. 34).

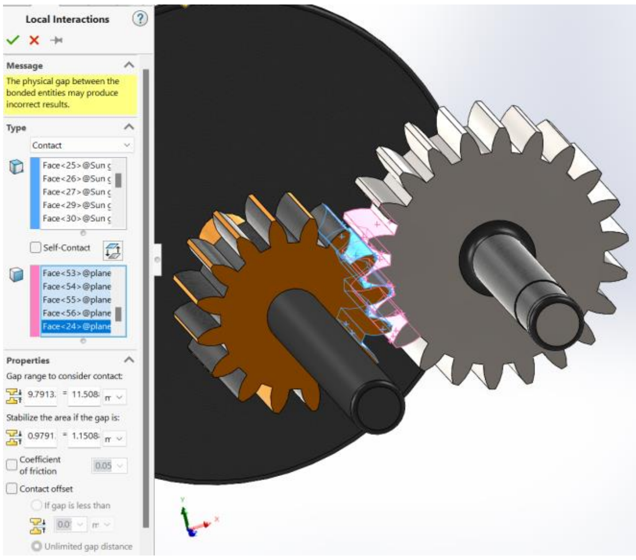


Figure 35*: Local interaction.*

A cylindrical fixture was then placed onto the Sun gear with the portion of the Planet gear being fixed (fig. 36)

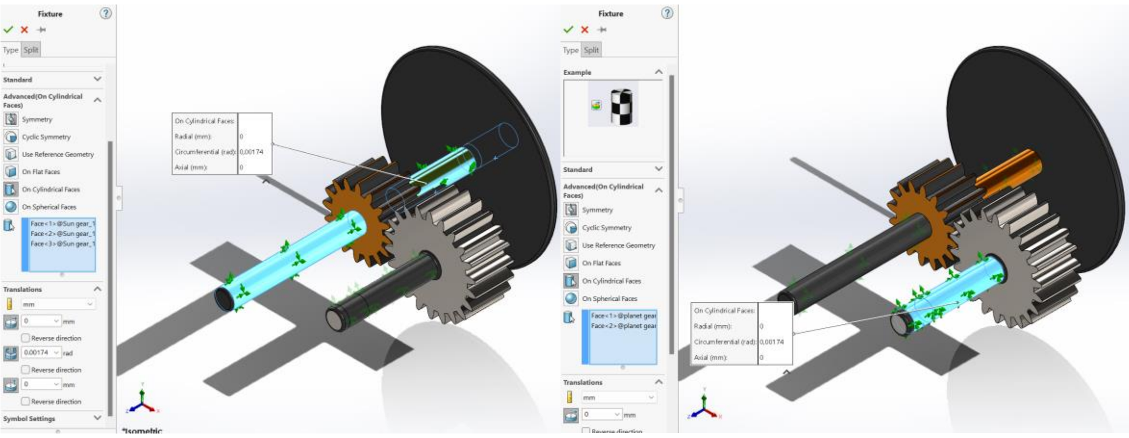


Figure 36*: Fixtures.*

A mesh was then created, and the study run.

3.4.3 Torque Analysis

A series of torque analyses were conducted between the Sun gear and a Planet gear. Due to the simplicity of this Planetary gear, and the fact that it’s a case study and not a manufactured product with an intended use purpose, a series of torques were applied on just a single Planet gear and the Sun gear, ranging from 1 to 60 Nm; that is, 1, 10, 20, 30, 40, 50 and 60 Nm. First, Fixtures were applied on parts that are not expected to move. Following this, from the “External Loads” option, a torque of 1nm was applied on the face of the Sun gear and the same for a face of the Planet gear with the force on the planet gear being oriented to the opposite direction. This was repeated for the other torques. The results were then placed on to an excel sheet from which a series of graphs were generated.

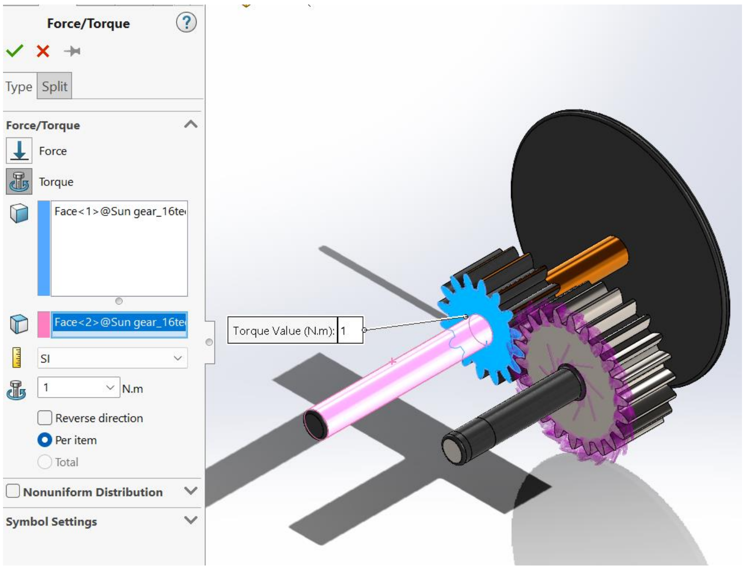


***Figure 37**: 1Nm torque.*

A mesh was created, and the study run.

4 Results

When the simulation is complete, the analyses receive Stress, Displacement, Strain and Factor of Safety results.

4.1 Contact analysis 1: Ring – Planet teeth

The results for the Ring-Planet gear contact analysis is as follows.

a. Stress:

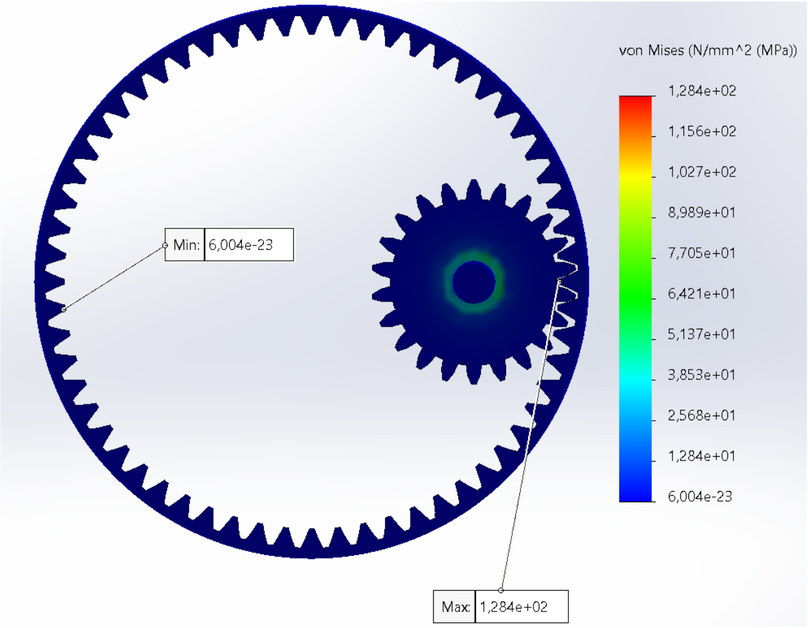


***Figure 38**:Contact analysis stress (Von Mises) result.*

b. Displacement:

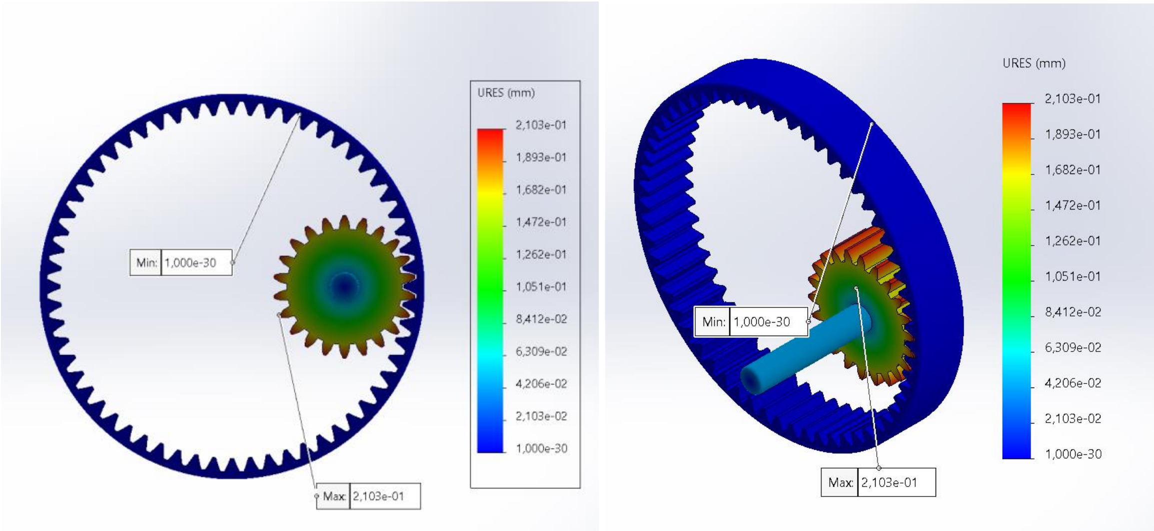


__Figure 39__: Contact analysis displacement result.

c. Strain:

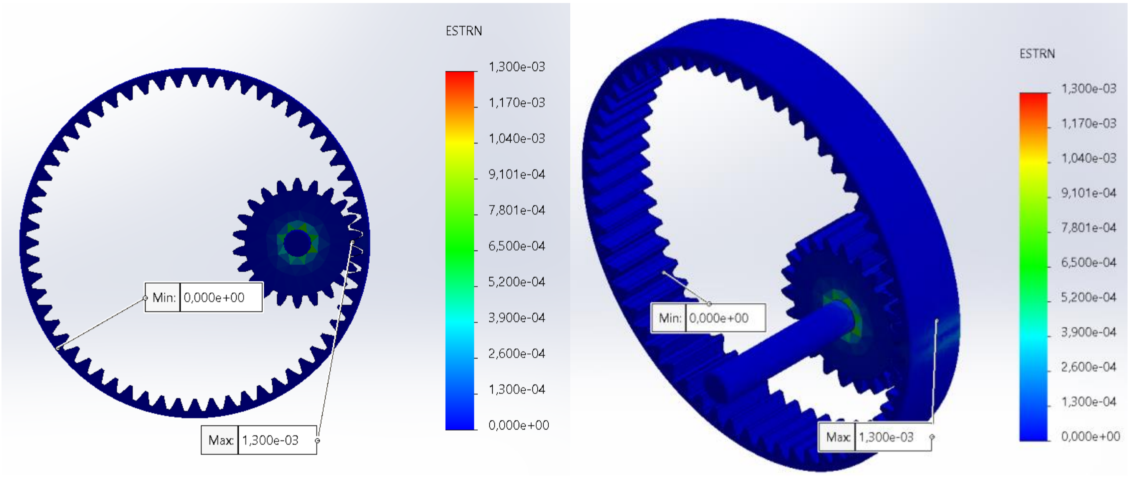


__Figure 40__: Contact analysis strain results.

d. Factor of Safety:

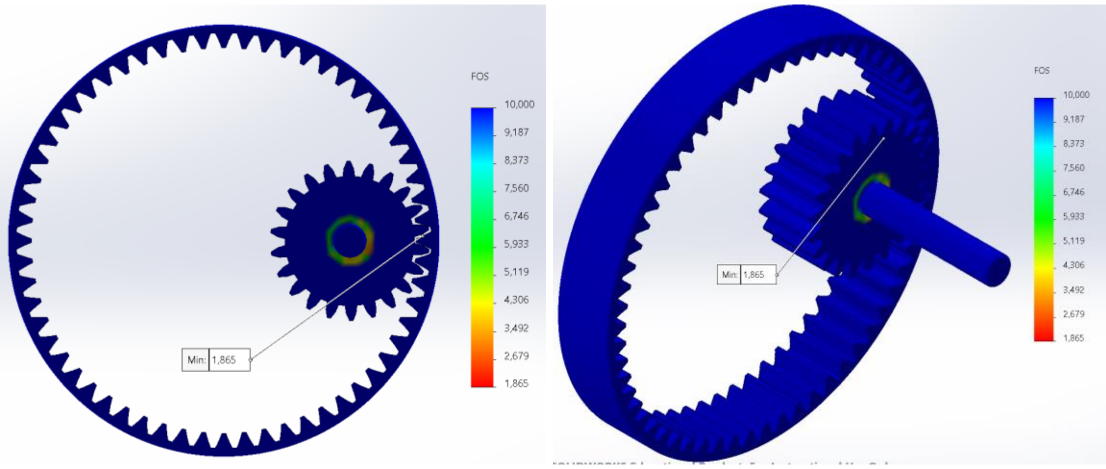


Figure 41: contact analysis Factor of Safety.

4.2 Contact Analysis 2: Planet – Sun gear teeth

The results for the Planet-Sun gear contact analysis are as follows:

a. Stress:

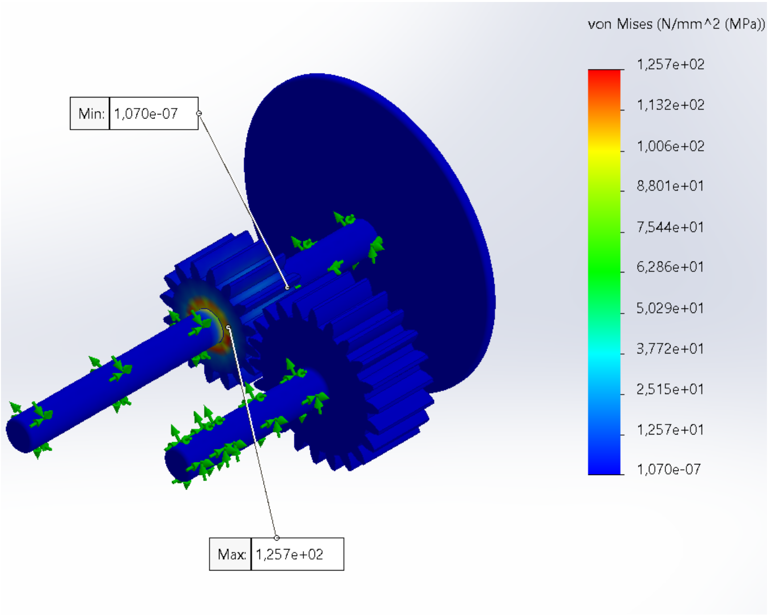


***Figure 42**: Contact analysis stress (Von Mises).*

b. Displacement:

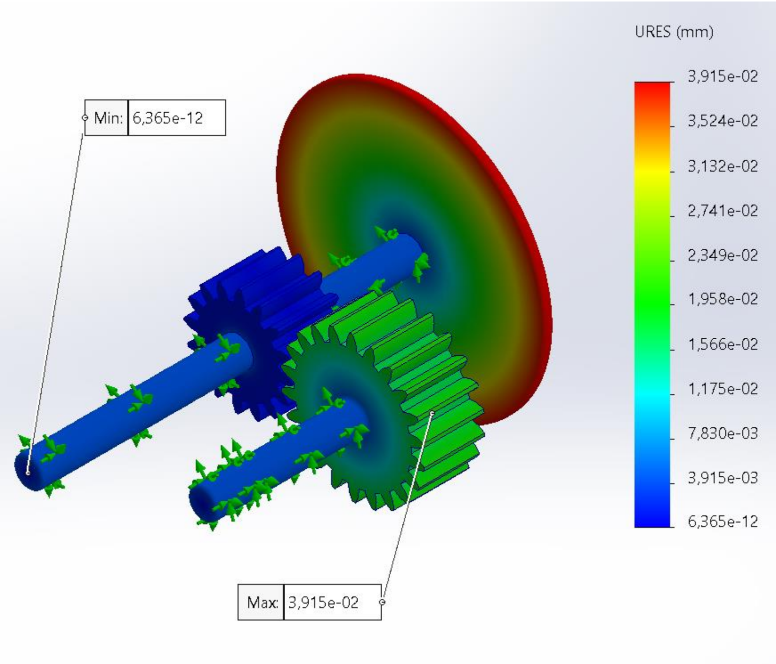


Figure 43*: Contact Analysis displacement.*

c. Strain

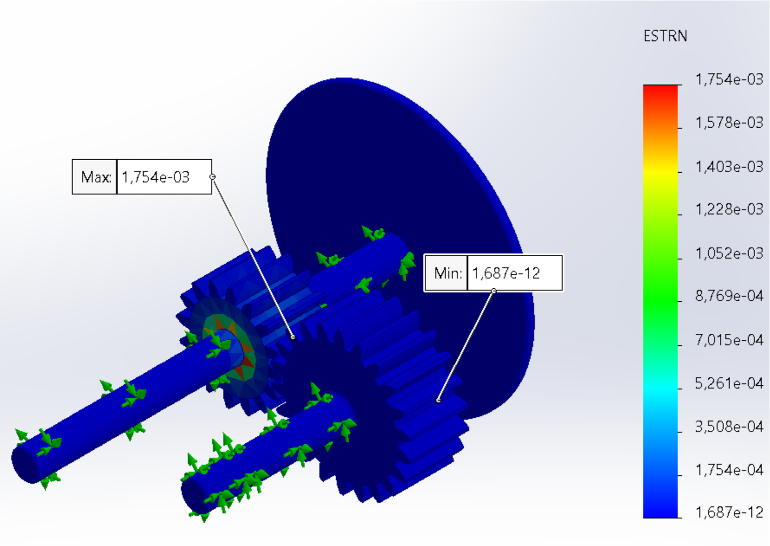


Figure 44*: Contact analysis strain result.*

d. Factor of Safety

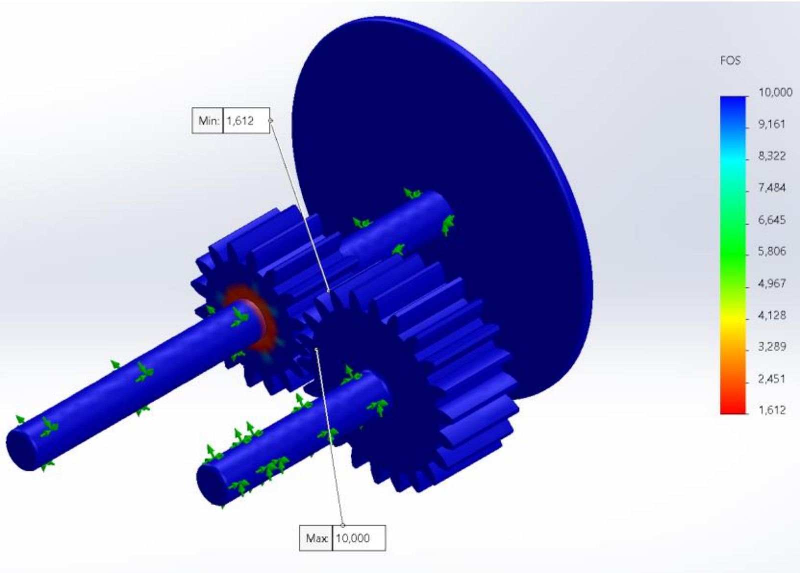


Figure 45*: Contact analysis Factor of safety.*

4.3 Torque Simulation

The following results for the torque simulations were produced by listing the maximum and minimum from each result into an excel sheet before plotting a graph. The factor of safety results plotted were only the minimum results and not the maximum as they weren't necessary.

Table 5: Torque simulation graphs excel sheet

Torque (Nm)	Max Stress, σ (MPa)	Maximum Displacement, δ (mm)	Maximum Strain, ε	FOS (Min)
1	2,818	0,00007344	0,00004509	69,56
10	28,18	0,0007344	0,0004509	6,956
20	56,36	0,001469	0,0009018	3,478
30	84,54	0,002203	0,001353	2,319
40	112,7	0,002937	0,001804	1,739
50	140,9	0,003672	0,002254	1,391
60	169,1	0,004406	0,002705	1,16

Each graph was created such that each result (i.e. "Max Stress" etc.) were placed in the y-axis and the Torque in the x-axis. An individual graph was made for each of the results.

The results for the torque test are as follows:

a. Stresses:

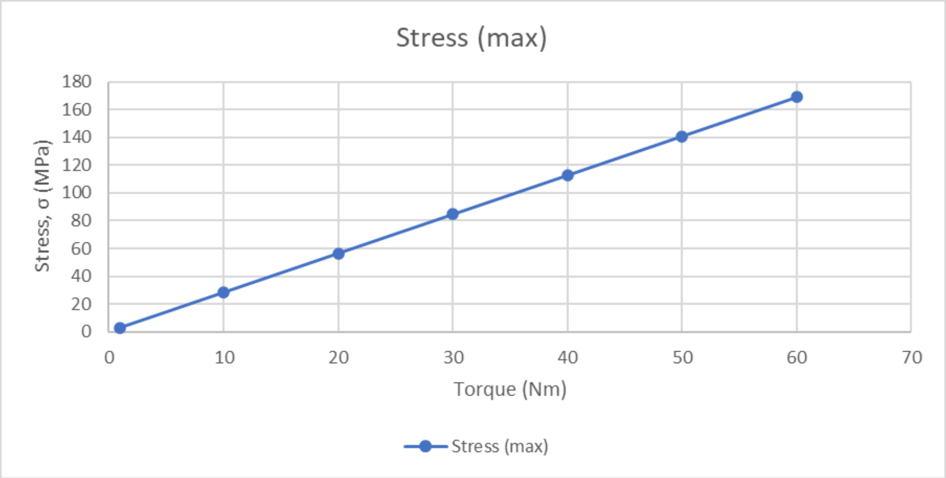


Figure 46*: Torque analysis maximum stress result.*

The graph shows the torque and stress to be directly proportional, in that as the torque increases so too does the stress. This is because as the torque creates a twisting force it generates corresponding shear stress that builds up in the gear.

b. Displacement:

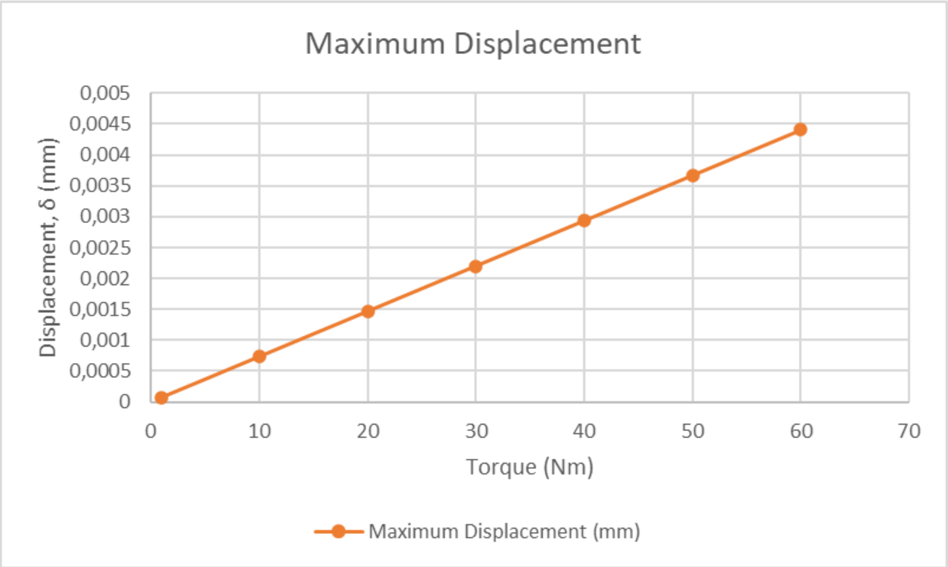


Figure 47*: Maximum displacement result.*

Similarly to the stress results, as the torque increases so too does the displacement in the gear. Again, this is due to the increasing shear stress placed on the gear by the torsion which causes increasing deformations and thus increased displacement. The displacement is, of course, quite small.

c. Strain:

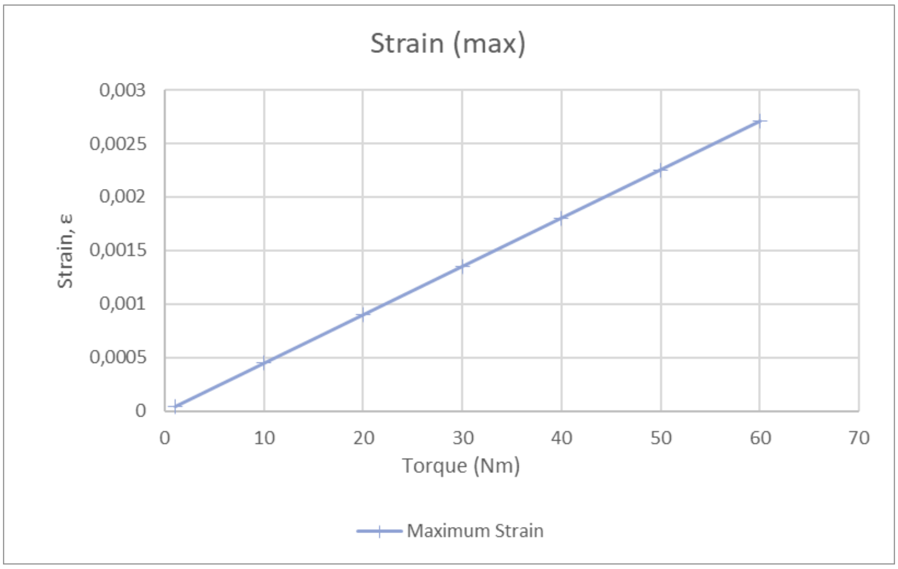


***Figure 48**: Maximum strain results.*

Once more a direct proportion is observed between the torque and the strain. Torque affects the strain results due to its influence on the stress state of the gear. From the graph it can be seen that as the torque increase so too does the strain; though the strain is quite small.

d. FOS:

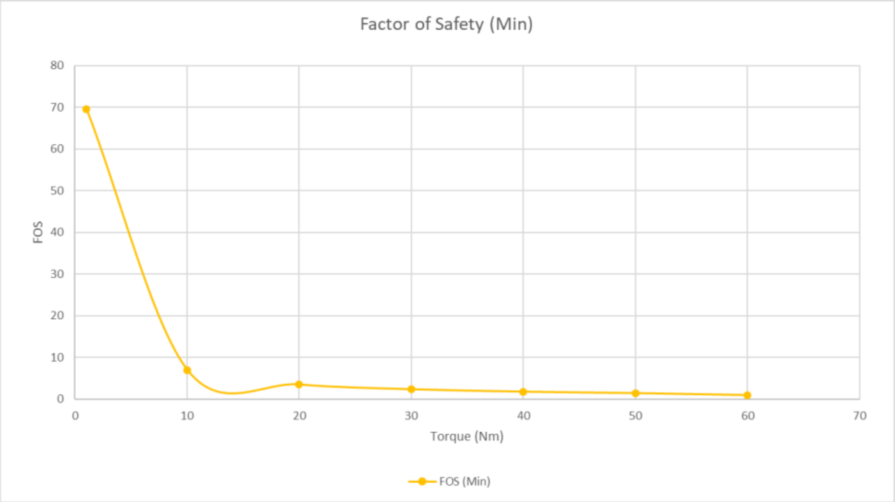


***Figure 49**: Factor of safety result.*

Factor of safety (FOS) is a numerical value that represents the margin of safety in a design or engineering analysis. A FOS is typically above 1, which can be seen in the graph. As the torque increases the FOS naturally decreases but even at 60Nm the FOS remained above one indicating that the gear could easily handle the maximum torque applied on to it during the study.

5 DISCUSSION

The objective of the thesis was to review and analyze the relevant literature on the design of machine elements, by focusing on gears as representatives of machine elements, their design principles, and design methods. Followed then by the choosing of a single gear type and the usage of computer-aided design (CAD) software to model and simulate the performance of the designed chosen gear under various operating conditions and loads. The thesis has achieved these goals with focus being given to the literary analysis of machine elements as a whole, as well as gears (as examples of machine elements) and a planetary gear (as an example of a gear). Likewise, the objectives for the design and simulation of the Planetary gear have been achieved with a clear and detailed design process on SolidWorks as well as successful contact analyses and torque simulation. For the analyses, the Contact analyses and the torque simulation showed four results each; Stress (MPa), Displacement (mm), Strain and Factor of Safety [FOS]. The torque simulation was done via a series of torques ranging from 1 MPa to 60 MPa to get a variety of results

The purpose of the contact analysis on the contacting teeth between the Ring-Planet and Sun-Planet was to identify and verify whether the teeth would mesh smoothly with little to no interferences, and thus whether the mathematical calculations conducted were correct. The first contact analysis results (Ring-Planet gear) showed a maximum stress (σ_{max}) of 128 MPa between the contacting teeth, a max displacement (δ_{max}) of 0,21mm, a max strain (ε_{max}) of 0,0013 and a minimum FOS of 1,9. The second contact analysis showed σ_{max} of 126 MPa, δ_{max} of 0,039mm, ε_{max} of 0,00175 and a min FOS of 1,6. The results show that not only is the Planetary gear safe but that the number of teeth for the Ring, Sun and Planet gears being 60, 16 and 24 respectively is proven to be a good choice.

The purpose of the Torque simulation was to analyse whether the Planet – Sun gear mesh could deliver on the expected function of a planetary gear by calculating how much torque they can withstand. The torque simulation results showed a series of results depending on the torque applied. For the lowest torque of 1Nm the results were σ_{max} of 2,8 MPa, δ_{max} of 0,000073mm, ε_{max} of 0,000045 and a min FOS of 69,6. The results for the max torque of 60 Nm was σ_{max} of 169,1 MPa, δ_{max} of 0,004mm, ε_{max} of 0,0027 and a min FOS of 1,16. This means that the portion of the Planetary gear is fully able to withstand the force applied by up to 60Nm of torque seemingly easily. The factor of safety results show that the portion of the gear are fully capable of handling the applied torques on their own and even more so if distributed across the whole gear.

6 CONCLUSION

Machine elements, known also as hardware, are important sets of components that allow for the running of machines. These elements include a range of components broadly categorized as “universal elements” such as springs, bearings, chains, gears, pins, belts, bolts and keys, and “special elements” which include turbine blades, aircraft propellers and crankshafts.

These small components are integral building blocks for most machines and are standardised to common sizes though customs do also exist. Among the machine elements gears are amongst the most widely used for a range of purposes within engineering as “transmission machine elements”; this is due to their myriad uses and ease of production.

A key machine element used in wide applications are gears. Gears come in different shapes and sizes that fall into four general categories spur, helical, bevel and worm. This thesis gave special focus to the Planetary gear which combines many of the general gear categories to make a complex yet valuable gear. Planetary gears are a simple yet effective way to visually show how gears, as machine elements, work in tandem to achieve a desired result, hence why it was chosen.

Planetary gears are made from different gears namely Ring, Carrier, Sun and Planet gear and are used widely in engineering and have the advantage of allowing both the input and output axes to be concentric, allowing for more compact gear arrangement. The thesis detailed the steps and process in designing a Planetary gear as well giving examples of possible analyses that can be studied. The Planetary gear underwent contact analyses and a torque test. The contact analyses on the Ring-Planet teeth contact points showed that the contact point between the two gears were able to run smoothly with little to no interferences, like wise for the Sun-Planet gear contact test. The results for the first contact analysis were σ_{max} of 128 MPa, δ_{max} of 0,21mm, ε_{max} of 0,0013 and a minimum FOS of 1,9. The second contact analysis showed σ_{max} of 126 MPa, δ_{max} of 0,039mm, ε_{max} of 0,00175 and a min FOS of 1,6.

The torque test on the Sun-Planet gears showed that the gears were able to fully withstand the torques applied from 1 to 60 Nm with the lowest torque of 1 Nm producing σ_{max} of 2,8 MPa, δ_{max} of 0,000073mm, ε_{max} of 0,000045 and a min FOS of 69,6. While the results for the max torque of 60 Nm was σ_{max} of 169,1 MPa, δ_{max} of 0,004mm, ε_{max} of 0,0027 and a min FOS of 1,16.

The Factor of safety did decrease drastically but it was still above 1 at 60Nm. Nevertheless, it's possible that the part would fail at or between 90 – 100 Nm; this can be inferred based on the trend and trajectory of the FOS graph. This is most likely due to the design of the Planetary gear but because the gear is a theoretical gear that would not go on to be produced, it is sufficient for the purpose of the thesis that is to show the design and simulation process of Planetary gears as representatives of gears as material elements. The design, modelling and testing of the Planetary gear, and the analysis results, should serve as a reference to the ease and usefulness of gears and machine elements as a whole, they are safe, simple in structure, easy to manufacture yet so vital.

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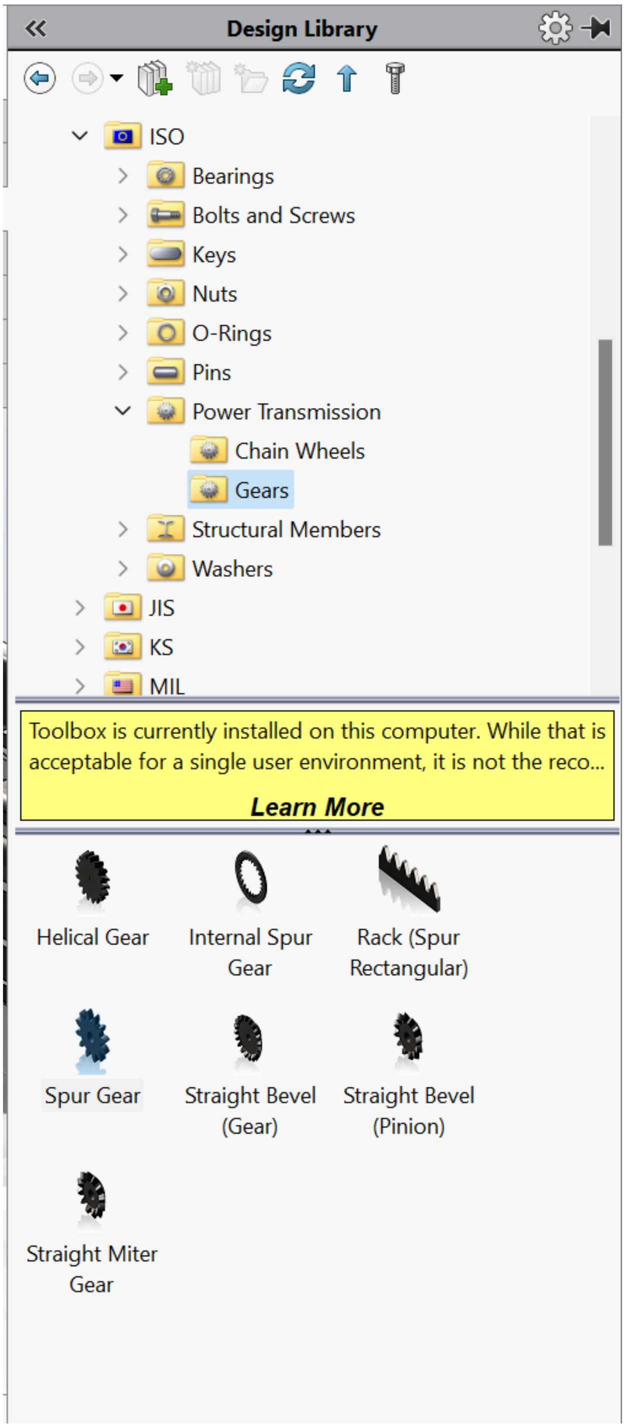
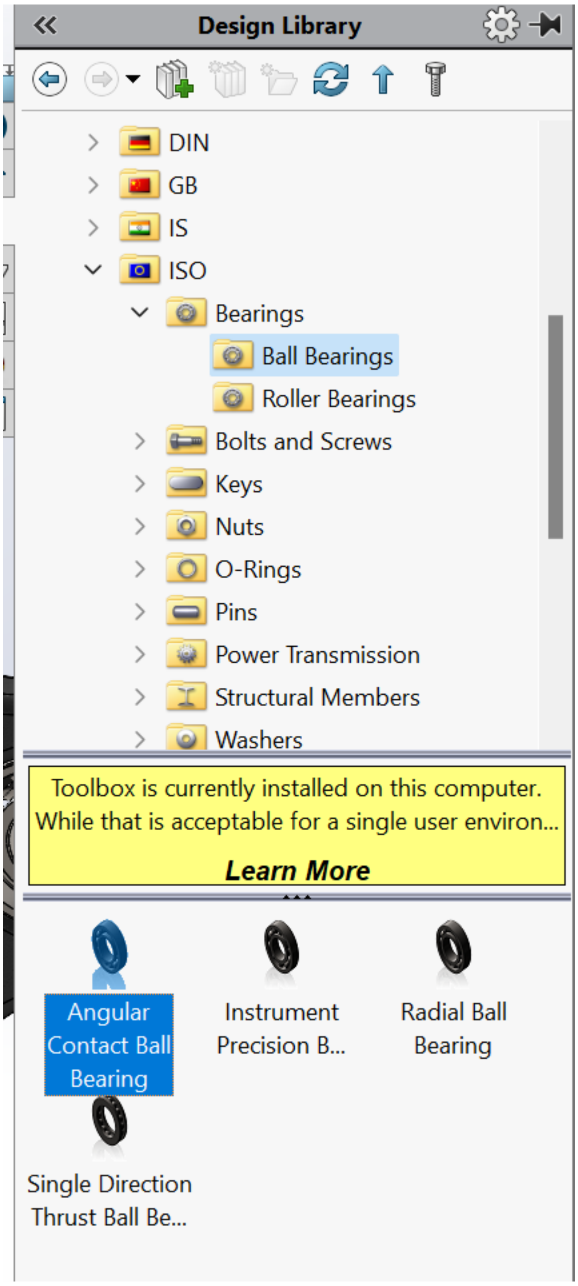
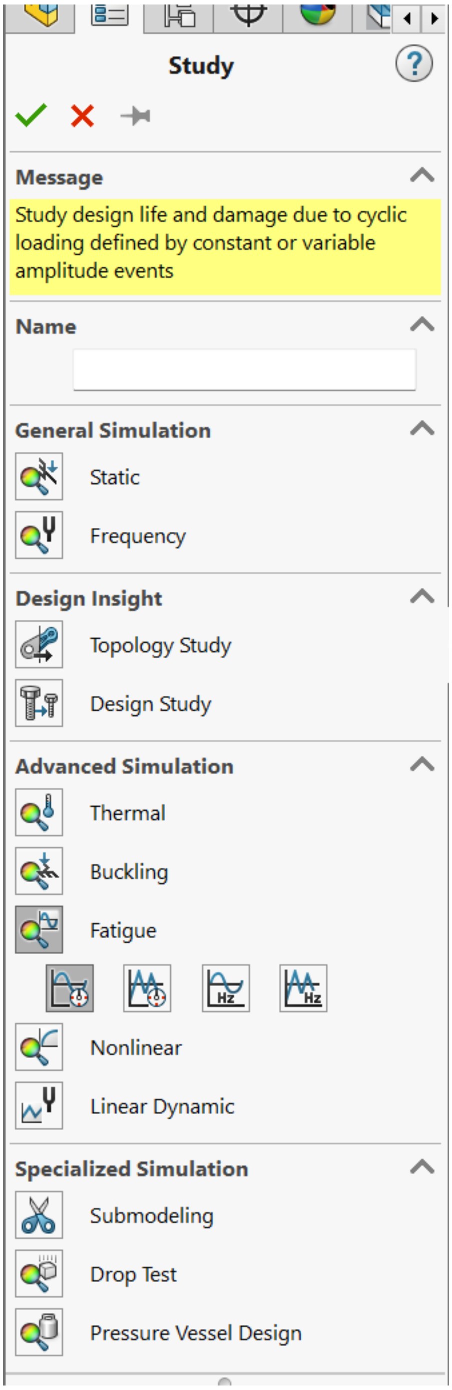
APPENDIX



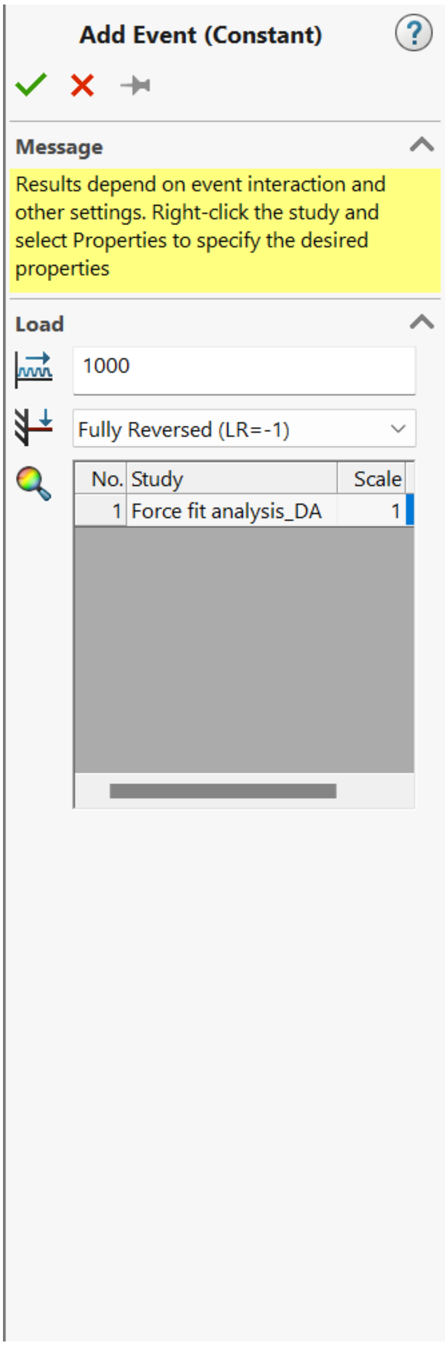
***Appendix 1**: Design library for gears*



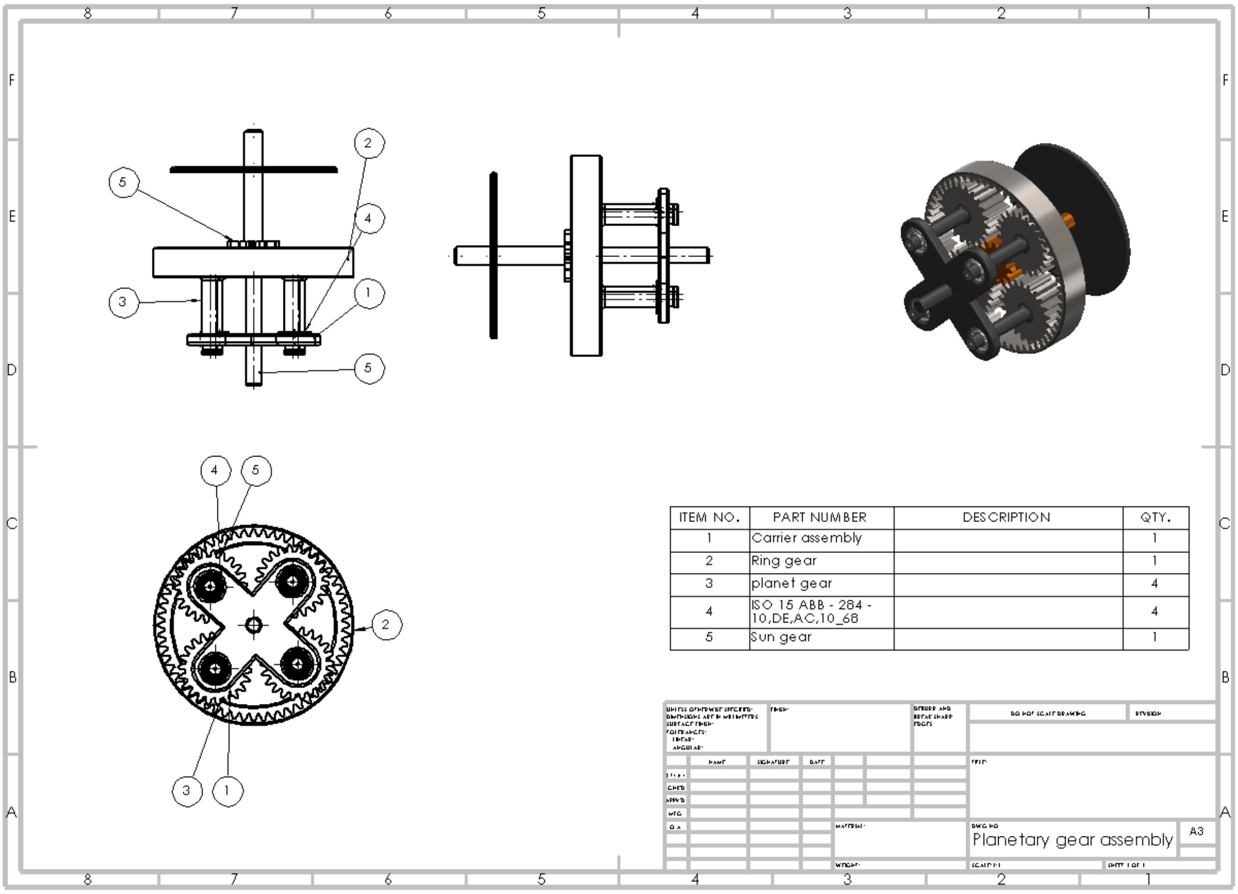
Appendix 2: *Ball bearing*



***Appendix* 3**: *Fatigue analysis*



Appendix 4: Add loading event



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Carrier assembly		1
2	Ring gear		1
3	planet gear		4
4	ISO 15 ABB - 284 - 10,DE,AC,10_68		4
5	Sun gear		1

Appendix 5: *Engineer drawing of assembly*